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ABSTRACT

This technical specialty course is one of thirty-five courses designed for use by two-year postsecondary institutions in five nuclear technician curriculum areas: (1) radiation protection technician, (2) nuclear instrumentation and control technician, (3) nuclear materials processing technician, (4) nuclear quality-assurance/quality-control technician, and (5) nuclear reactor (plant) operator trainee. This course, Principles of Process Instrumentation, contains eight modules: Temperature-Sensing Devices: Glass-Bulb Thermometers: Temperature-Sensing Devices: Thermocouples: Temperature-Sensing Devices: Resistance Thermometers: Temperature-Sensing Devices: Pyrometers: Basic Principles of Flow Measurement: Pressure-Sensing Devices: Flow-Sensing Devices: Differential-Pressure Flowmeters: and Flow-Sensing Devices: Linear Flowmeters. Each module follows a typical format including the following sections: introduction, module prerequisites, objectives, subject matter, exercises, materials, procedures, data tables, reference materials, and tests. (A master index and suggested program planning guides are also available--see CE 026 856 and CE 026 639-642.) (LRA)

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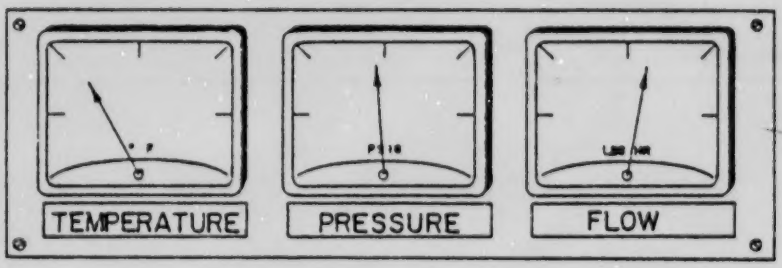
NUCLEAR TECHNOLOGY

Series

MODULE 3-1 TEMPERATURE-SENSING DEVICES: GLASS-BULB THERMOMETERS



PRINCIPLES OF
PROCESS INSTRUMENTATION

COURSE 3

U.S. DEPARTMENT OF HEALTH, EDUCATION & WELFARE
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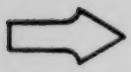
COURSE MODULES

COURSE 3 PRINCIPLES OF PROCESS INSTRUMENTATION



MODULE 3-1	Temperature-Sensing Devices: Glass-Bulb Thermometers
MODULE 3-2	Temperature-Sensing Devices: Thermocouples
MODULE 3-3	Temperature-Sensing Devices: Resistance Thermometers
MODULE 3-4	Temperature-Sensing Devices: Pyrometers
MODULE 3-5	Basic Principles of Flow Measurement
MODULE 3-6	Pressure-Sensing Devices
MODULE 3-7	Flow-Sensing Devices: Differential-Pressure Flowmeters
MODULE 3-8	Flow-Sensing Devices: Linear Flowmeters

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INTRODUCTION

Process instrumentation in a steam electric generating plant normally includes those instruments used to measure and control the three most important operating parameters of a plant: temperature, pressure and flow. Nuclear instrumentation in a nuclear power plant differs from process instrumentation in that it indicates performance by measuring nuclear radiation associated with the reactor. In many instances, information derived from process instrumentation is used in association with nuclear instruments for calibration and the like.

There are many additional process instruments associated with steam electric generating plants. These include measurement and control equipment for chemical process variables (acidity, pH, viscosity, and so on), air flows in heat and ventilation systems, pneumatic systems, relative humidity, and the chloride content of boiler water. But most of these instruments are quite similar to those found in most other chemical production plants.

Temperature is the most commonly measured parameter in any power plant. Available to an instrumentation system designer are the usual industrial methods of measuring temperature. These include, for example, glass-bulbs, resistors, thermocouples and pyrometers, as well as more recently developed instruments that incorporate thermistors and other solid-state devices.

No other single property ranks as high in measuring requirements as does temperature. Temperature determines, in part, the lifetime and integrity of a given material, the efficiency and safety of plant operations, and the environmental impact (and economics) of a specific process.

Within a nuclear power plant, the temperatures of gases, reactor coolant effluents, steams, metal surfaces, switchyard transformers and a myriad of other important components and process indicators must be monitored.

This module specifically discusses glass-bulb thermometers (in terms of their principle of operation, the concept of temperature, establishment of temperature scales) and their types and constructions, accuracy and characteristics in use, calibration, typical usage, advantages and disadvantages and thermowells. Also, the hierarchy of standards is introduced along with the basis for its use.

Later modules in this course will discuss additional methods of measuring temperatures and the other important parameters of a power plant, such as pressures, fluid levels and flow characteristics.

MODULE PREREQUISITES

The student should have successfully completed courses in the following areas: basic physics, mathematics and basic chemistry. Students are encouraged to do advance reading on nuclear systems and power plants. Previous experience in normal laboratory practices is required, especially laboratory safety principles.

Course 4, "Heat Transfer and Fluid Flow" should be taken concurrent with this course.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define or describe the following terms:
   - Process instrumentation.
   - Nuclear instrumentation.
   - Temperature.
   - Three process variables.
   - Sensor.
   - Four temperature scales.
   - Accuracy.
   - Precision.
   - Parallax.
   - Response time.
   - Secondary standard.
2. Sketch and identify the following:
   - Principal features of an instrumentation system.
   - Principal features of a glass-bulb thermometer.
   - Principal features of a thermowell.
3. Given the conversion formulas and specific temperature values, convert from one temperature to another (three types of scales).
4. Explain basic principles and operation of a glass-bulb thermometer.
5. Describe construction and utilization of the two basic types of thermometers (as discussed in this module).
6. Describe construction, operation and use of a wet-bulb thermometer.
7. List five disadvantages and four advantages of glass-bulb (mercury) thermometers.
8. Describe sources of errors in the use of glass-bulb thermometers.

9. Explain hierarchy and purpose of standards.
10. Calibrate a glass-bulb thermometer; establish calibration curve over the 0°C to 100°C range.

INSTRUMENTATION PROCESS VARIABLES

The systems, components and materials which make up a nuclear power plant have certain measurable physical and chemical properties that, if exceeded, could compromise the safety, efficiency or designed lifetime of an operating plant. The three basic process variables considered most important include:

Temperature.
Pressure.
Flow.

(Level is considered a pressure variable.)

In a nuclear-powered steam electric generating plant, these variables relate directly to the need for ensuring that thermal energy of fission is adequately removed and transported to steam generators and turbines; otherwise, fuel may be damaged (or melt), requiring an immediate, expensive and prolonged shutdown of the plant.

(In a fossil power plant, these same variables are important because the boiler's tubes must be cooled sufficiently.)

Temperature, pressure and flow are observable and measurable parameters, and process instrumentation measures them in both fossil and nuclear power plants. Also, these parameters are used to determine the power level of all steam electric plants, by using what is known as a heat balance. These data, in turn, are used to control the plant within predetermined and specific ranges of temperature, pressure and flow. Note: In a nuclear power plant, one additional parameter is measured directly: neutron flux

(or intensity) relating to reactor power output. Instrumentation used to obtain this information, along with its transmission to control and safety systems, is classified as "nuclear instrumentation."

Every measure starts with a sensor, a device that is sensitive and specific to the property to be measured. Some sensors obtain a readable signal very simply, such as the expansion of mercury in a glass-bulb thermometer (where the displacement in a capillary filament is observed against a scale).

COMPONENTS OF A TYPICAL INSTRUMENTATION SYSTEM

The basic components of a typical instrumentation system (Figure 3-1-1) usually include a sensor, a detector or transducer (called the primary element), an intermediate transmitter and link, and a receiver (or readout) device

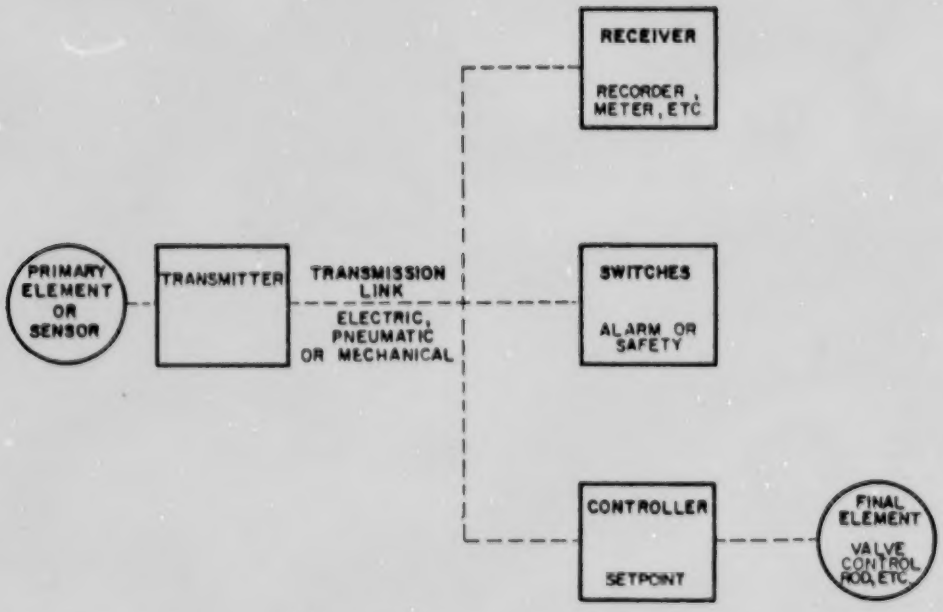

Figure 3-1-1. Typical instrumentation system components.

that displays quantitative information. Attached to these components may be controllers or other control elements.

CONCEPT OF TEMPERATURE

The first process variable to be discussed is temperature, the most commonly measured variable in any power plant. This variable may be thought of as the degree of hotness or coldness of a material or an environment in reference to a specific scale. When the material is heated, its molecules increase their rapidity of vibration. And, process instruments, which do not measure the temperature of a material directly, measure the effect of temperature on some property of the material.

One such effect could be either the linear or the volumetric expansion of the material as it becomes hotter.

TEMPERATURE SCALES

To quantitatively describe the magnitude of a process variable, one must have a standard unit of measurement and a scale. For temperature, the unit is called a degree. The range and magnitude of the temperature or scale may be expressed in any one of four temperature scales (Figure 3-1-2):

Celsius (Centigrade).
Fahrenheit.
Kelvin.
Rankine.

The Celsius scale (°C) is constructed by using the freezing and boiling points of water under standard pressure conditions as the respective fixed points of zero and 100, with 100 equal divisions (degrees) between.

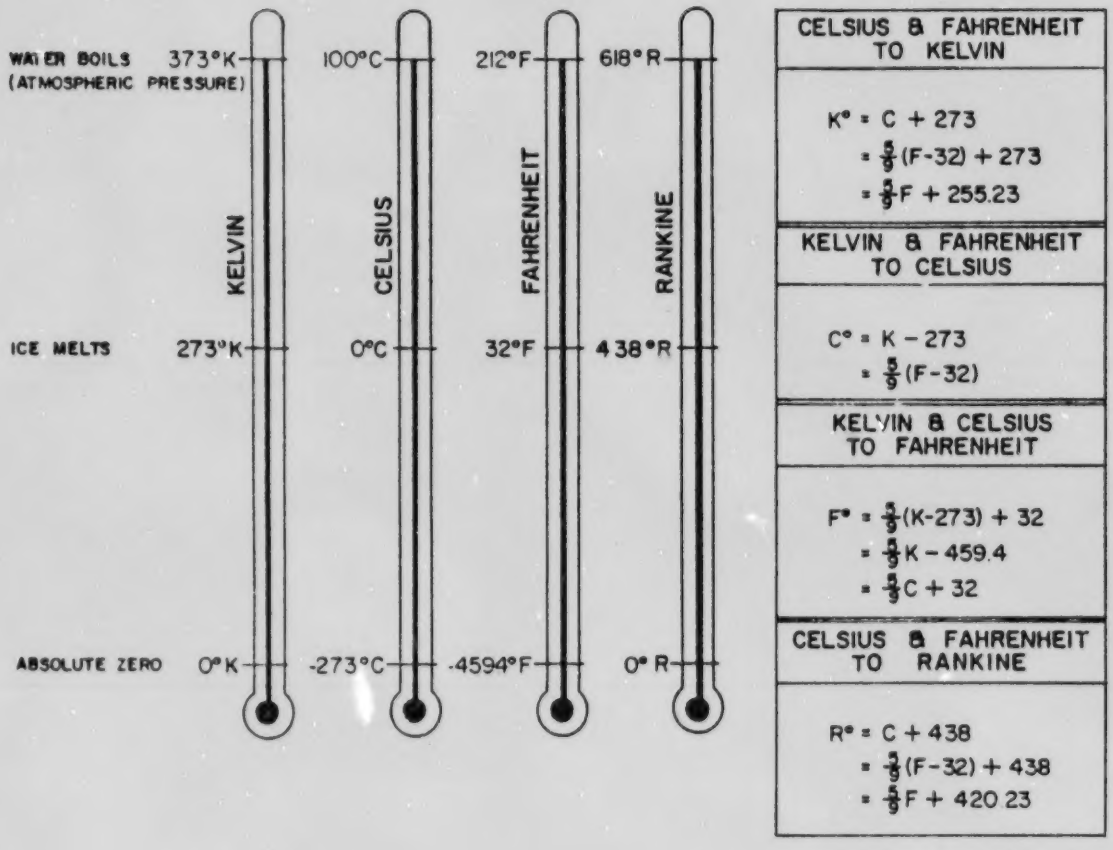

Figure 3-1-2. Comparison of the four temperature scales.

The Fahrenheit scale (°F) uses 32° as the freezing point of water and 212° as the boiling point, with 180 equal divisions between.

The absolute or Kelvin (°K) scale is constructed with its zero point at absolute zero, or 273 Centigrade degrees below the freezing point of water. By definition, the Kelvin

scale is set as 273°K (the triple point of water where water coexists as a solid, gas and liquid) and 373.15°K (the boiling point of water as steam and liquid).

The Rankine (°R) scale is the conversion of the Fahrenheit scale to the absolute scale. Thus, absolute zero may be expressed as -273°C, 0°R, 0°K or -459.4°F. For most calculations and industrial purposes, the conversion equations in Figure 3-1-2 are of acceptable accuracy.

The Celsius scale (the metric system's standard) is used in almost all scientific and international work. It should become more common in future technical work as the United States converts to the metric system. Fixed points for this scale are defined in the International Practical Temperature Scale of 1968 (IPTS-68).

PRINCIPLES OF OPERATION

The principle that most gases, liquids and solids expand as their temperature increases is the operating basis of a glass-bulb thermometer - such volumetric expansion can be measured directly as displacement.

The glass-bulb (or liquid-in-glass) thermometer is one of the most widely used temperature sensors in science and industry. It consists of a glass envelope, an expandable liquid and an indicating or reference scale. The envelope consists of two parts: a large volume, thin-walled bulb filled with a liquid and a stem of relatively small bore diameter (capillary) filled with an excess of the liquid, with its top level coinciding with the temperature of the liquid. Adjacent to or imprinted on the stem is a scale.

TYPES OF THERMOMETERS

Glass-bulb thermometers are generally found in three forms:

All glass, with etched or enclosed scale (Figure 3-1-3).

Tube, with separate scale (Figure 3-1-3).

Industrial (Figure 3-1-4).

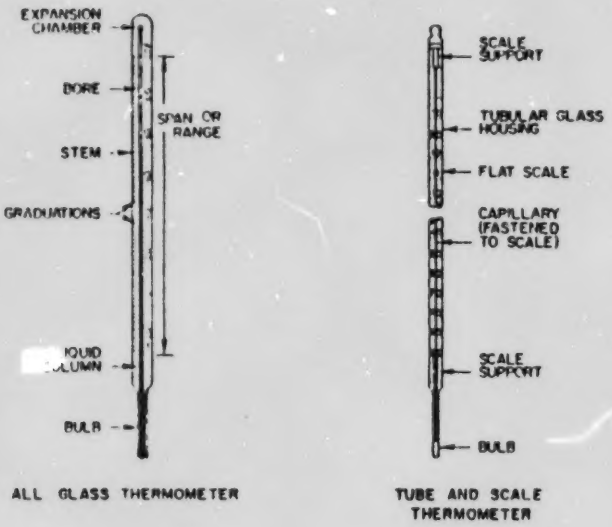

Figure 3-1-3.
Glass-bulb thermometers.

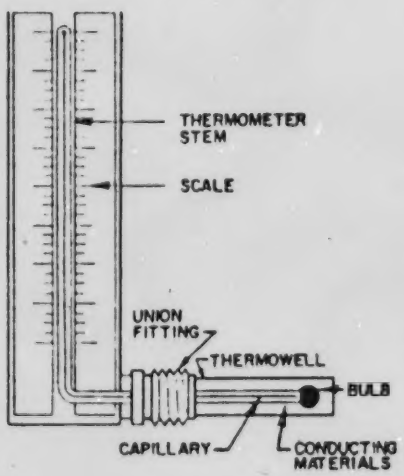

Figure 3-1-4.
Industrial thermometer.

One other type of glass-bulb thermometer is the "wet-bulb." This thermometer is normally used to determine the amount of moisture in the air (relative humidity). It is based on the reduction of temperature on a thermometer caused by the evaporative cooling of water.

When two identical thermometers are fastened together (Figure 3-1-5) and one is covered with a water-saturated wick, the wet thermometer measures "wet-bulb temperature" when the pair is whirled. The whirling produces rapid air flow over the wick, which attains maximum evaporative cooling. (This arrangement is called a "sling psychrometer.")

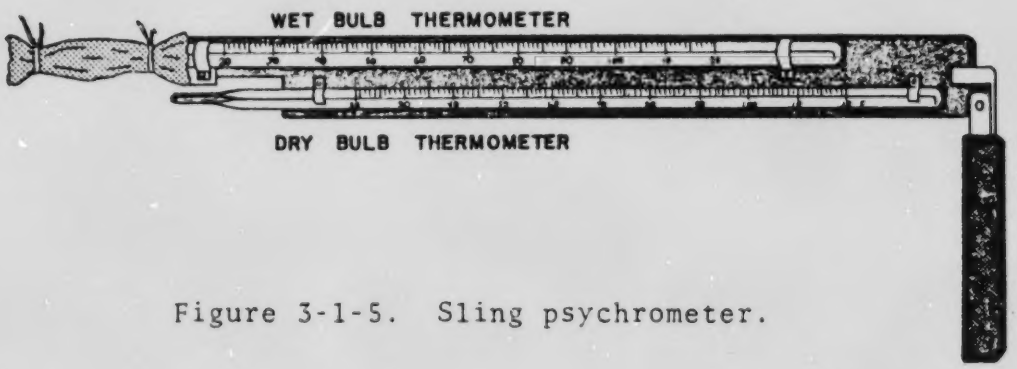

Figure 3-1-5. Sling psychrometer.

Relative humidity is determined by comparing instrument reading with a psychrometric chart (Figure 3-1-6).

The difference between the dry- and wet-bulb temperatures is called the "spread." It is this spread which affects the efficiency of cooling towers and other air and evaporative heat sinks. The greater the spread, the higher the efficiency of the process.

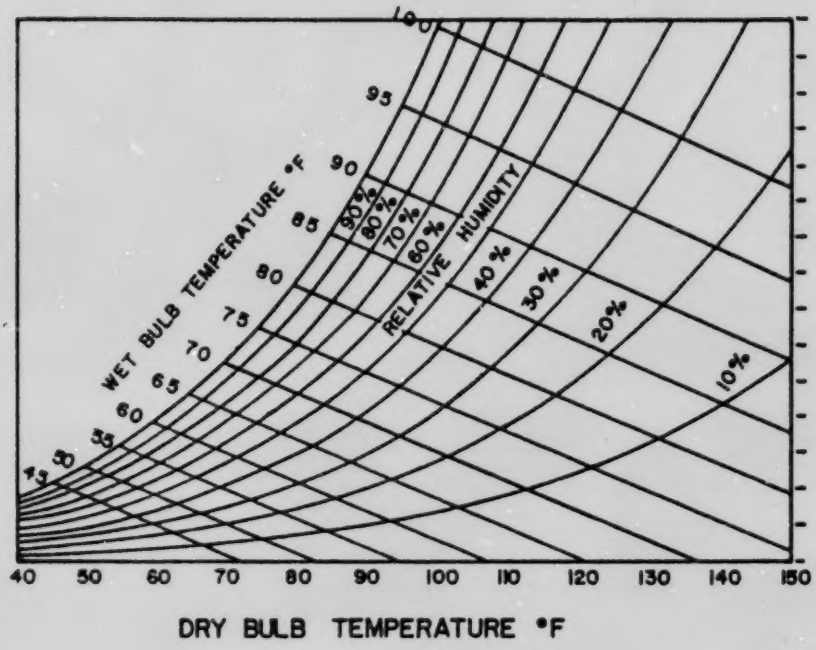

Figure 3-1-6. Psychrometric chart.

LIQUIDS USED IN GLASS-BULB THERMOMETERS

Various liquids may be used in glass-bulb thermometers. Mercury serves best in most higher temperature measurements - it is the most accurate because it has a nearly linear coefficient of expansion (i.e., its volume change is proportional to the temperature change). The broad temperature span between freezing and boiling points of mercury provides a range sufficiently great for most uses.

Industrial type thermometers must be constructed to withstand more severe applications (greater vibration, more structural contact and other physical abuses). Glass-bulb thermometers, encased in metal, permit immersion of the thermom-

eter into measurable fluids. A coupling is provided for mounting in a tank, pipe or duct.

Industrial thermometers are distinguished by tube construction (straight or angle), by case size (5, 7, 9, 10 or 12 inch) and by bulb exposure to environment (such as a bare bulb encased in a metal chamber, with the chamber mounted in a well).

Alcohol and pentane may be used to extend the range of glass-bulb thermometers below the freezing point of mercury (-39°C). To extend this range above the boiling point of mercury, the capillary may be sealed under high pressure by using nitrogen or carbon dioxide. Special glass for the stem is required for extra high-temperature applications.

The useful temperature ranges for the more common glass-bulb thermometers are given as follows:

Mercury	-39 to 600°C
Mercury alloy	-60 to 120°C
Organic liquids	-200 to 230°C

MEASUREMENTS AND CHARACTERISTICS IN USE

The terms most commonly used for describing instrument output acceptability (or the results of a calculation) are accuracy and precision. The purpose of a measurement is to obtain the true value (the actual change) of a process variable, within limits, by comparing it with a standard or reference. Accuracy can be defined, therefore, as the conformity of a measured value to a standard value or known true value.

"Precision" refers to the reproducibility of a measure-

ment, and this can be inferred from a possible denotation given for the quantity. For this reason, precision is sometimes associated with the smallest scale division (or reading error).

Laboratory type thermometers are usually accurate to within about 0.1% of their range spans; industrial thermometers are only accurate to within about 1.0% of their range spans.

Accuracy of the glass-bulb or liquid-in-glass thermometer is dependent, in part, on the readability of a column of liquid, as well as on the stability of the glass (uniformity of stem) and on parallax.

Parallax is the apparent displacement caused by the line of vision not being normal to the scale (Figure 3-1-7).

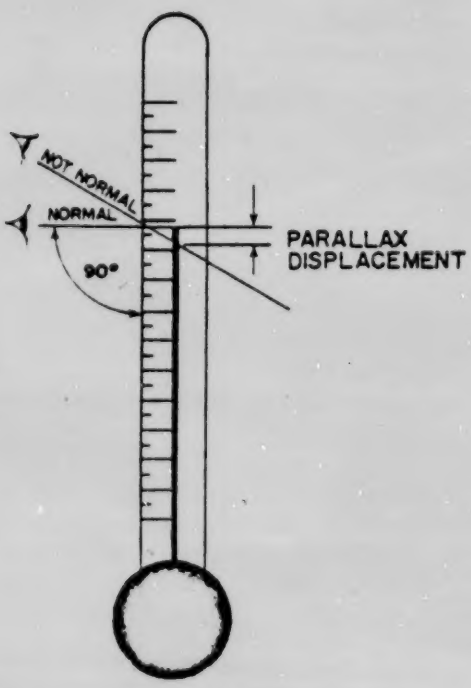

Figure 3-1-7.
Parallax illustrated.

An error is also introduced if the thermometer is not immersed to the depth for which it was calibrated.

Other characteristics of glass, which may affect accuracy, include memory effect (hysterisis) - enlargement of the bulb at high temperature, which persists to some degree when thermometer is used later at significantly lower temperatures.

Slight pressure changes are not normally significant in closed bulb thermometers. Accuracy may be compromised by time lags while rapid changes in temperatures are occurring (Table 3-1-1).

TABLE 3-1-1
ACCURACY OF GLASS-BULB MERCURY THERMOMETERS
(LABORATORY TYPES)

Temperature Range °C	Accuracy °C
0 - 150	0.1 - 0.2
0 - 300	0.2 - 0.5
+300 - 500	0.5 - 1.0

MODES OF USE

Glass-bulb thermometers are designed for use in various modes:

"Total immersion" of bulb and liquid portion of capillary stem in medium.

"Complete immersion" of thermometer in medium.

"Partial immersion" of thermometer in medium.

Mercury-in-glass thermometers are normally graduated for total immersion use unless otherwise specified by a demarcation on the stem. When the stem of a total-immersion thermometer can be only partially immersed (e.g., an opaque solution), a correction (k) for stem emergence error must be applied (Figure 3-1-8):

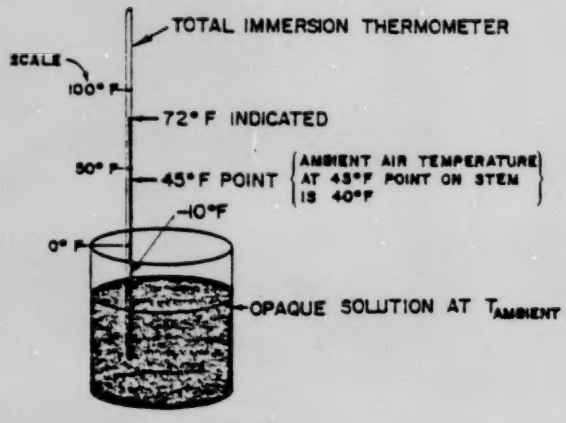

Figure 3-1-8.
Sample situation requiring thermometer correction for stem emergence.

$$t_{true} = t_{indicated} + k$$

Equation 3-1-1
(Equation = Eq.)

where

k = correction, °F (added where the stem is cooler than the bulb).
= $9 \times 10^{-5} D (t_{ambient} - t_{indicated})$

D = number of degrees of exposed mercury, °F.

$t_{ambient}$ = ambient temperature at mid portion of exposed stem, °F.

$t_{indicated}$ = thermometer reading, °F.

t_{true} = temperature, °F, corrected for stem emergence error.

The accuracy of measured temperatures may be improved by proper use of thermometers. A time lag must be considered when a temperature to be measured is changing or has changed. Response time of thermometers, influenced chiefly by fluid medium and by size of thermal well, is defined as the time required for the thermometer to reach 63.2% of the measured medium's true value after a change in temperature occurs in that medium (Figure 3-1-9).

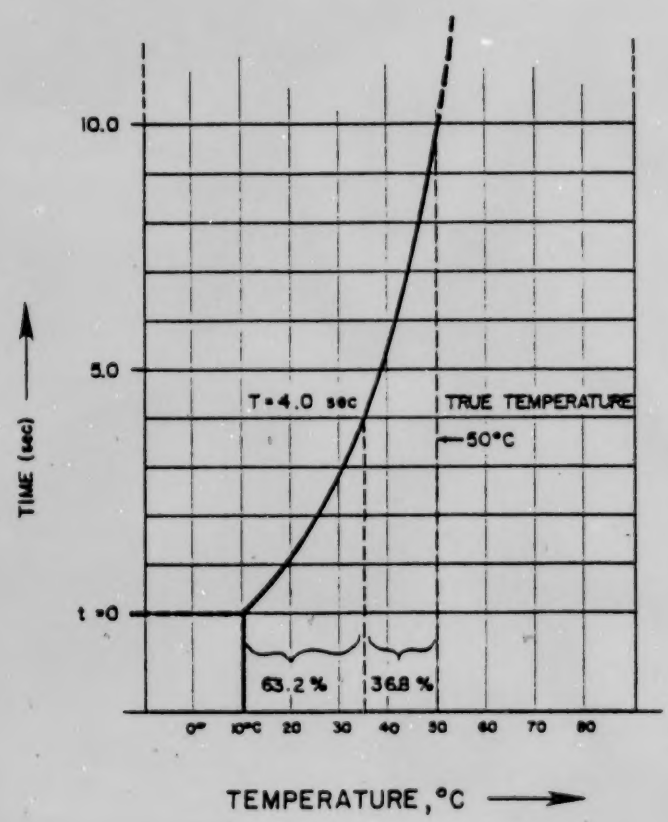

Figure 3-1-9.
A typical time-response recorder trace.

Operational errors in thermometer use usually result from failure to ensure a thoroughly mixed (thermally equilibrated) medium, or from placing the thermometer in a stagnant region of a flowing medium.

Parallax, also of continual concern, can be minimized by using a reflective background on the stem.

Another source of error relates to the improper depth of immersion, mentioned earlier.

ADVANTAGES AND DISADVANTAGES OF GLASS-BULB THERMOMETERS

The advantages of glass-bulb thermometers (specifically, mercury filled) include:

Low cost.
Simplicity.
Ease of checking for physical damage.
No supporting systems or power supplies requirement.
Experience in use and familiarity.
Broad temperature span.
Nonwetting characteristics.
Introduction of no impurities.

Disadvantages include:

Relative fragility.
Generally limited range (to ~ 600°C).
Lack of facility in remote reading.
Low-temperature coefficient of expansion.
Corrosiveness upon fracture.

SELECTION AND USAGE

The choice and usage of glass-bulb thermometers in power plants is generally governed by the characteristics of process and by the other equipment used in the plant. In

nuclear plants (except in laboratories) mercury glass-bulb thermometers are NOT used. Mercury can amalgamate (alloy) and corrode other metals. Prevention of the release of radioactive fission products from irradiated fuel or waste storage is the first line of defense in a nuclear plant. Mercury could violate the barriers established in these systems.

In fossil power plants, industrial thermometers are used in those low-pressure and medium-temperature environments normally associated with auxiliary equipment, but less extensively in other manufacturing facilities.

Overall, glass-bulb thermometers are essentially confined to laboratory and special in-plant use. Thermocouples and resistance type sensors (discussed in Module 3-2, "Temperature Sensing Devices: Thermocouples," and Module 3-3, "Temperature Sensing Devices: Resistance Thermometers,") are generally used in power plant process measurements.

PROTECTION TUBES AND THERMOWELLS

"Protection tube" is the classification given to a broad type of devices used to both protect and improve the accuracy and response of sensing elements.

A protection tube protects a sensor from such hazards as corrosion, high pressure, physical shock, electrical effects and contamination. It also provides a "well" into which the sensor may be placed to bring it into more immediate contact with the medium whose temperature it is sensing.

A thermowell (or "well") is the most common of such devices found in a power plant. A well (Figure 3-1-10) is

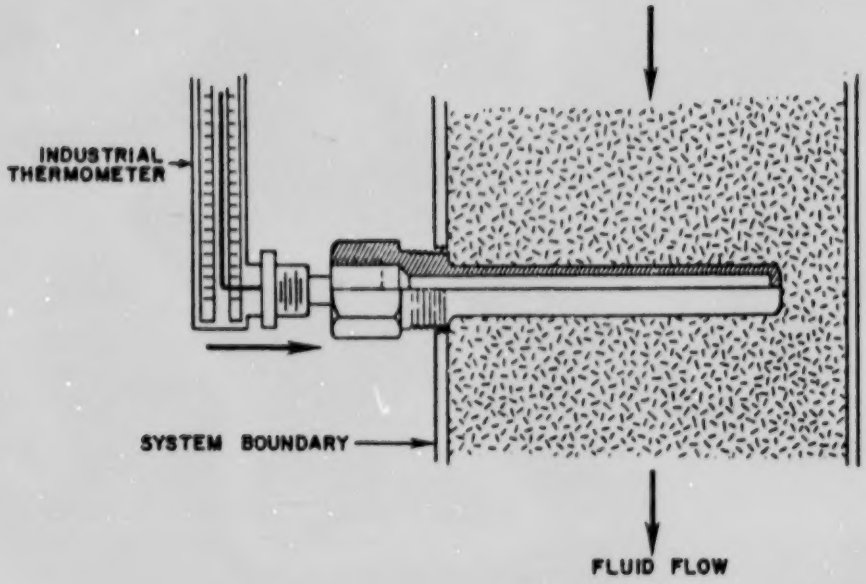

Figure 3-1-10. A typical standard threaded thermowell.

any structure closed on one end, open on the other and designed to receive a thermometer bulb or other temperature measuring device (e.g., thermocouple or resistance thermometer). The well projects into a vessel, pipe or duct, and is generally fastened by a pressure-tight, leak-tight connection.

Selection of protection tubes and thermowells is based on specific physical considerations:

Corrosive effect of bimetal coupling between well and vessel.

Location in vessel (in terms of pressure).

Dynamic forces.

Temperature.

Thermal conductivity.

The thermowell must be touching the temperature-sensing element to shorten time response and improve accuracy.

To minimize temperature lag, a thermowell is sometimes filled with low-viscosity, high-thermal-conductivity liquid (such as water, alcohol or kerosene). For temperatures greater than 600°F, tin, mercury or solder alloys are frequently used.

An additional and equally important feature of the thermowell is that it provides a means of removing the sensor from the medium (for repair, replacement or calibration) without disturbing system or plant operation.

While temperature may be the most common measurement, it can also be the most misleading. A temperature sensor inserted into a thermowell measures "the" temperature, but it may not be the correct temperature. Successful temperature measurements depend on the selection of a "typical" temperature, since temperature gradients of varying degree exist in any situation. Actually, judgment in the proper location of sensors and interpretation of data is essential. And, meaningful temperature measurements require that the sensor be in thermal equilibrium with the sensed medium's temperature.

CALIBRATION AND THE HIERARCHY OF STANDARDS

Basic to the accuracy of a measurement is the documented fact that an instrument sensing the information must itself be accurate; i.e., when a thermometer reads 100°C, there must exist a confidence that indeed it is measuring a temperature of 100°C (to within a certain degree of accuracy). The traceability of any unit of measure to the unit, as defined by the National Bureau of Standards (NBS), is the basis for assuring the accuracy of any measurement. The number of intermediate steps between the end user and NBS

depends on the accuracy requirements. The carrying out of calibration responsibilities normally rests with an outside calibration laboratory or the respective facilities at a plant.

Within a laboratory, some instrument represents the traceable, or known, accuracy standard measure of the measurable variable (e.g., temperature, pressure and resistance). These items then become the local primary standard for that unit at that facility.

In some cases, this local primary standard may be used to calibrate test equipment, but more often it is used to calibrate other standards, called secondary standards or working standards.

Depending on the needed accuracy, the local primary standard may be calibrated either by an independent laboratory or directly by NBS. Each transfer of measure units degrades to some extent the transferred value of the standard.

The National Bureau of Standards issues monographs and similar documents on calibration procedures and their hierarchy. NBS Monograph 90, Calibration of Liquid-in-Glass Thermometers, is such a procedure. These monographs, and the American Society for Testing and Material (ASTM) standards, should be referred to when carrying out calibrations.

Primary standards are expensive, and their integrity and stability must be maintained and assured. They should not be used for routine measurements. In the transfer of calibrations, the reference standard used to calibrate process instrumentation should normally have an accuracy of four to ten times that required by the process instrument. The final basis of acceptance of an instrument for plant use is

the "acceptance criteria" defined by the instrument manufacturer or by the plant engineer.

Accuracy of a glass-bulb thermometer is quoted by its manufacturer. To obtain a "traceable" to NBS can be an unnecessary expense if the manufacturer's certification is adequate. As a rule of thumb, glass-bulb thermometers can be read to their finest scale, with interpolation to the next half or tenth scale. Table 3-1-2 approximates the accuracies of three types of these thermometers.

TABLE 3-1-2
ACCURACY OF GLASS-BULB THERMOMETERS

Class	Range, °C	Accuracy
All Glass	-200 to +600	Usually one scale division ± 0.05°C
Tube & Scale	-40 to +260	Usually one scale division ± 0.05°C
Industrial (Mercury)	-40 to 648	Usually one scale division ± 0.05°C

Thermometers may best be compared with primary or secondary standards. It may also be desirable to have a fixed-point apparatus available for occasional checking of the calibration [e.g., an ice bath for a low-range thermometer and melt-point samples (NBS) like tin (231.9°C) and antimony (630.5°C) to serve as high-temperature references].

METHODS OF CALIBRATION

The formal calibration of a thermometer may best be accomplished by repeated comparison with either a primary or secondary standard thermometer over the full range of the instrument: Choice of intervals within the range of calibration is dictated by the nominal span of the thermometer's intended use (e.g., if a particularly critical function were to occur at 250°C, such as starting of pumps, calibration intervals should normally be made at about this point).

Selecting a suitable calibration may be a function of any number of factors, including these most significant ones: First, of course, are quality of equipment and care exercised in its construction, use and calibration. Second is the use of laboratory and industrially proven procedures [such as ASTM Standard E77, Standard Method for Verification and Calibration of Liquid-in-Glass Thermometers (Figure 3-1-11)]. For many practical purposes, a fixed-point apparatus is available, such as a simple ice-salt bath. Third, care and protection of the standards themselves (calibration standards) - this equipment should never leave its permanent location, except for its own calibration.

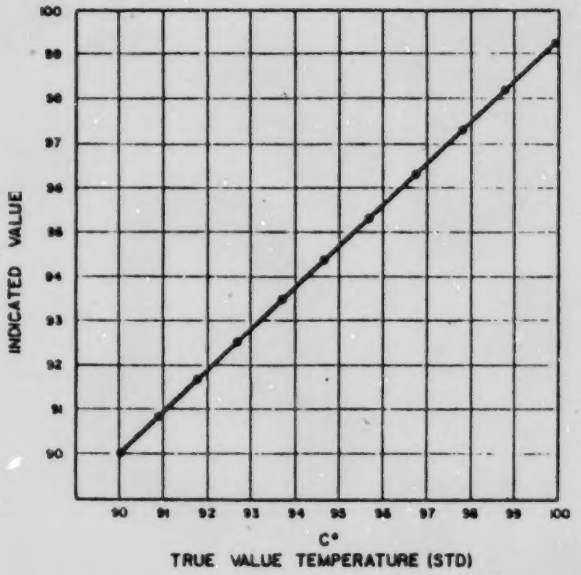

Figure 3-1-11. Typical glass-bulb thermometer calibration curve.

EXERCISES

1. Define absolute zero.
2. In the winter, persons are encouraged to maintain their home thermostats at 65°F during the day and 60°F or lower at night. Locate these temperature values on the Celsius scale.
3. A total immersion thermometer is used to measure temperature of a beaker of oil. The thermometer reads

150°C when the number of degrees of exposed mercury column is 100 and temperature at middle of exposed portion of stem is measured to be 20°C. Determine true temperature of oil.

4. Use Figure 3-1-11: determine corrected reading of thermometer when its indicated temperature, when totally immersed, is 95°C.
5. Indicate the melting and boiling points of water (at standard atmospheric conditions) in degrees Rankine, Celsius, Fahrenheit and Kelvin.

MATERIALS

1 Dewar flask (approximately 2.0 liter). (Note: Commercial or laboratory kits for the procedures are recommended.)
1 Viewing telescope of 10x magnification and mount.
1 Siphon tube.
1 Ice shaving/crushing machine.
1 NBS traceable thermometer (< -10° - 100°C), secondary standard, total immersion type.
1 Test thermometer, identical to above.
1 2-3 blade stirring shaft and drive.
1 Felt covered top for flask.
1 Metal flask holder.

GLASS-BULB THERMOMETER CALIBRATION

PART I: ICE-BATH COMPARATOR METHOD (ICE FIXED POINT).

1. Set up a mercury glass-bulb thermometer (as shown in Figure 3-1-12), but without standard thermometer and stirrer.

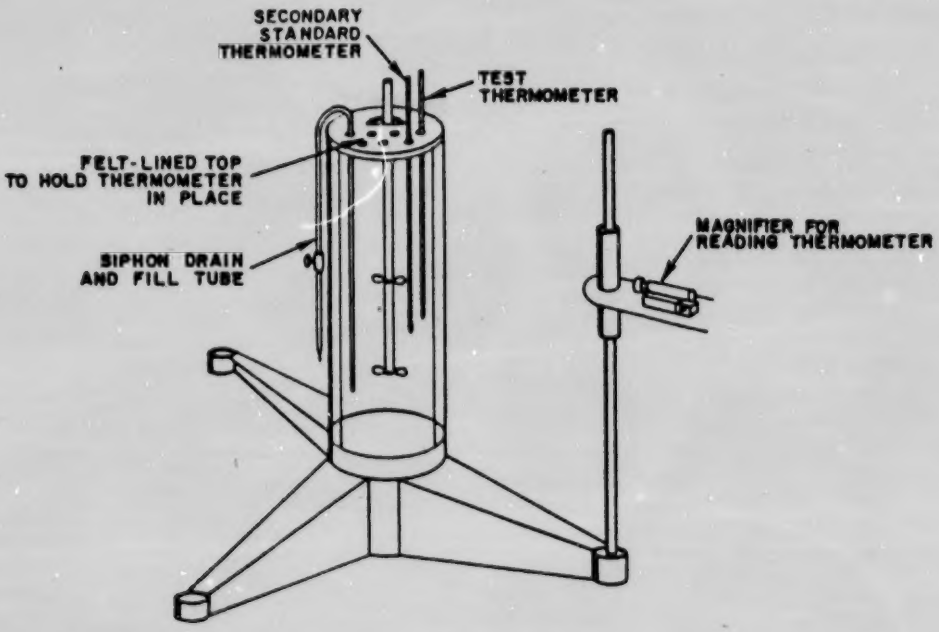
SECONDARY STANDARD THERMOMETER
TEST THERMOMETER
FELT-LINED TOP TO HOLD THERMOMETER IN PLACE
SIPHON DRAIN AND FILL TUBE
MAGNIFIER FOR READING THERMOMETER

Figure 3-1-12. Experimental arrangement for ice- and water-bath comparator method. (Note: stirrer blades set to give downward thrust.)

2. Select clear pieces of ice; crush into small pieces; do not contaminate by direct contact with hands.

3. Fill Dewar flask with crushed ice; add sufficient distilled water, but do not float ice.
4. Insert thermometer to be calibrated, and siphon tube; cover thermometer with water to above 0°C graduation.
5. Drain off water as ice melts and add more crushed ice and water.
6. After three minutes, raise thermometer a few millimeters, tap stem gently until successive readings agree within one-tenth of a division; use magnifier to take readings.
7. Record data from five successive readings on Data Table 3-1-1.
8. Perform succeeding steps as indicated on Data Table 3-1-1.
9. In space provided on Data Table 3-1-1, explain any unusual variations in data.

Part II. CALIBRATION AT TEMPERATURES OTHER THAN FIXED POINTS.

1. Set up mercury glass-bulb equipment (as shown in Figure 3-1-12), but without secondary standard and test thermometers.
2. Draw cold, clean tap water, with a temperature as cool as practical; fill Dewar flask full.
3. Insert siphon tube, stirrer, secondary standard and test thermometers.
4. Start stirrer motor; adjust thermometer's mercury columns to one centimeter above felt-lined top.
5. After five minutes, tap stems gently until successive readings on each thermometer agree with previous readings within one tenth of a division; use magnifier to take readings; make successive readings on both thermometers.

6. Record data from three such readings (taken at one-minute intervals) on Data Table 3-1-2.
7. Drain one-half cup of water from Dewar; add one-half cup of hot tap water.
8. Repeat 4 through 7 four more times; enter data on Data Table 3-1-2.
9. Plot average of readings A_1, A_2 and A_3 for standard and for test thermometer on graph paper. Repeat for readings B through E.
10. Compare deviation throughout range of readings.

DATA TABLE

DATA TABLE 3-1-1

ICE BATH FIXED POINT

Reading No.	Fixed Pt Value (A)	Thermometer Reading (R)	Deviation (A-R)=X	X^2
1	0.0°C			
2	0.0°C			
3	0.0°C			
4	0.0°C			
5	0.0°C			
N=5				ΣX^2=

Average Error = $\sigma = \frac{\Sigma X^2}{N}$ = _____

Explain any possible reasons for the difference between the true and indicated 0°C value.

DATA TABLE 3-1-2

CALIBRATION OF THERMOMETERS AT OTHER THAN FIXED POINTS

Reading No.	Standard °C	Test °C	Time
A1	_____	_____	_____
A2	_____	_____	_____
A3	_____	_____	_____
	Avg_____	Avg_____	
B1	_____	_____	_____
B2	_____	_____	_____
B3	_____	_____	_____
	Avg_____	Avg_____	
C1	_____	_____	_____
C2	_____	_____	_____
C3	_____	_____	_____
	Avg_____	Avg_____	
D1	_____	_____	_____
D2	_____	_____	_____
D3	_____	_____	_____
	Avg_____	Avg_____	
E1	_____	_____	_____
E2	_____	_____	_____
E3	_____	_____	_____
	Avg_____	Avg_____	

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TEST

Read each question carefully. Be sure your responses give the specific information each question requires. Your answers should be brief. Use the backs of the test if you need more space.

1. What is process instrumentation? What is nuclear instrumentation?

2. List the three most important process variables.

   a. _____

   b. _____

   c. _____

3. Give one reason it is important to measure the three process variables accurately in a nuclear-powered steam electric generating plant.

4. Sketch and label the basic components of a typical instrumentation system.

5. Define temperature.

6. What do process instruments measure with respect to temperature?

7. The four temperature scales are Celsius, Fahrenheit, Kelvin, and Rankine. Compare each scale as to the temperature at which water boils, temperature at which ice melts, and absolute zero by filling in the chart below.

SCALE	ABSOLUTE ZERO TEMPERATURE	TEMPERATURE AT WHICH WATER BOILS	TEMPERATURE AT WHICH ICE MELTS
Rankine			
Celsius			
Fahrenheit			
Kelvin			

8. What is the principle of operation of the glass-bulb thermometer?

9. What is the principle of operation of the "wet bulb" thermometer? For what purpose is the "wet bulb" thermometer used?

10. Describe how a sling psychrometer measures relative humidity.

11. What does the term "spread" mean? What is the relationship between spread and the efficiency of air and evaporative heat sinks?

12. Why is mercury a good liquid to use in glass bulb thermometers when measuring high temperatures?

13. What is meant by the accuracy of a measuring instrument?

14. What is meant by precision of a measuring instrument?

15. Describe three factors that affect the accuracy of the glass bulb or liquid-in-glass thermometer.

16. Define response time of a thermometer.

17. What is one factor that can have a major effect on response time?

18. List five disadvantages of the mercury-filled glass bulb thermometer.

a.

b.

c.

d.

e.

19. List four advantages of the mercury-filled glass bulb thermometer.

a.

b.

c.

d.

20. Why are mercury glass bulb thermometers confined only to laboratory and special in-plant use in nuclear plants?

21. What is a thermowell? What is one purpose for which a thermowell is used?

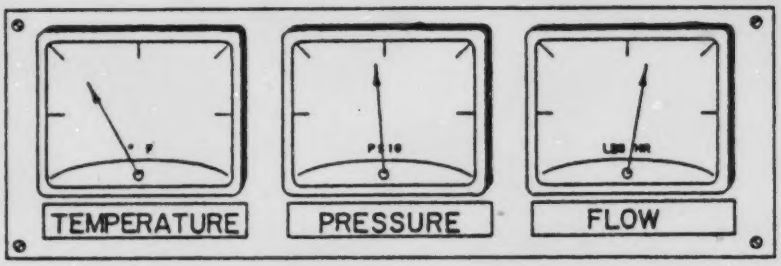
22. How is the "formal" calibration of a thermometer usually accomplished?

_____

_____

NUCLEAR TECHNOLOGY

MODULE 3-2 TEMPERATURE SENSING DEVICES: THERMOCOUPLES



PRINCIPLES OF
PROCESS INSTRUMENTATION

COURSE 3

COURSE MODULES

COURSE 3 PRINCIPLES OF PROCESS INSTRUMENTATION

MODULE 3-1	Temperature-Sensing Devices: Glass-Bulb Thermometers
MODULE 3-2	Temperature-Sensing Devices: Thermocouples
MODULE 3-3	Temperature-Sensing Devices: Resistance Thermometers
MODULE 3-4	Temperature-Sensing Devices: Pyrometers
MODULE 3-5	Basic Principles of Flow Measurement
MODULE 3-6	Pressure-Sensing Devices
MODULE 3-7	Flow-Sensing Devices: Differential-Pressure Flowmeters
MODULE 3-8	Flow-Sensing Devices: Linear Flowmeters

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INTRODUCTION

High rates of energy production in steam electrical generating plants require that temperatures be accurately measured and controlled. They cannot be measured directly, but rather must be indirectly or remotely sensed through some physical property that changes with temperature.

This module discusses the thermocouple method of temperature measurement. This method is based upon the principle that if two unlike metals are joined to form a complete electrical circuit, a current flows when the junction points are at different temperatures.

Principal advantages of the thermocouple for measuring temperatures include:

Versatility of application.
Rapidity of response through wide ranges of temperature.
High accuracy.
Durability.
Relatively low cost.
Convenience of recording or reading remotely.
Simplicity of application for regulation and control of temperature.

MODULE PREREQUISITES

The student should have successfully completed a basic electricity course and be familiar with normal safe laboratory practices, as well as Module 3-1, "Temperature Sensing Devices: Glass-Bulb Thermometers."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define or describe the following:
   - Thermocouple.
   - Constantan.
   - Seebeck effect.
   - Peltier effect.
   - Null potentiometers, null-balancing.
   - emf.
   - Standard cell.
   - Reference-junction compensation.
   - Chromal-alumel.
   - Galvanometer.
   - Thermopile.
   - Sheath.
2. Explain basic principles and operation of a thermocouple, including Seebeck and Peltier effects.
3. Describe, with the aid of a circuit diagram, thermocouple measurements; use millivoltmeter method.
4. Describe, with the aid of a circuit diagram, thermocouple measurements; use potentiometer method.
5. Explain purposes of standard cells and reference-junction compensation in thermocouple measurements.
6. List six factors to be considered in selection of thermocouples for particular applications.
7. Predict, from appropriate table, emf for a given thermocouple system and temperature.
8. Explain theory behind (and applicability of) series-connected and parallel-connected thermocouples.

9. Sketch a sheathed thermocouple; describe implications of differences between grounded and ungrounded sheaths.
10. Given thermocouple wire and ice-bath, connect a thermocouple system; use both a millivoltmeter and a potentiometer.
11. Calibrate a thermocouple over the range 0° to 100°C; use a calibrated glass-bulb thermometer.

TEMPERATURE MEASUREMENT

Temperature influences properties and performances of almost every material in a power plant, and the measurement of temperature usually must be made under a variety of circumstances, with a wide variety of instruments and methods. Temperature is not measured directly, but rather by its effects. These effects include:

Linear or volumetric expansion of materials.
Resistance changes in electrical conductors.
Thermal or optical aspects of radiation.
Thermoelectric effects.

Accurate temperature measurements are not necessarily easy to make, even with sensitive instrumentation. Different methods must be employed, depending upon many factors, including:

Material to be measured (solid, liquid or gas).
Steady-state or transient conditions.
Reliability and accuracy required.
Temperature range.
Type of read-out device used.
Cost allowed.
Environment.

Temperature-sensing devices discussed in this module are generally resistant to high radiation fields, such as may be found in a nuclear plant; however, the radiation could degrade insulation inside a device. Also, it could introd as a result of internal neutron and gamma heati actors should be considered when evaluating r

A thermocouple has the widest useful range and application of any temperature-sensing device because of its accuracy, ruggedness, reliability, adaptability to remote readouts and ability to generate an electrical signal that can be conveniently employed in control applications.

Temperatures in the range of 300°F to over 3000°F can be measured by a commercial thermocouple.

PRINCIPLES OF OPERATION

Thermocouples, essentially, are pairs of different or dissimilar metals, connected at both ends. When the two ends are subjected to different temperatures, an electrical potential is established between them, and a current flows in the closed circuit.

When one junction is maintained at a fixed temperature, called the reference temperature (e.g., that of melting ice), the other (sensing) junction may be used as the thermometer. The temperature of the sensing (hot) junction can be determined from available tables, if the difference in potential (voltage) between the junctions and the thermocouple material properties are known.

An ordinary thermocouple circuit (Figure 3-2-1) might

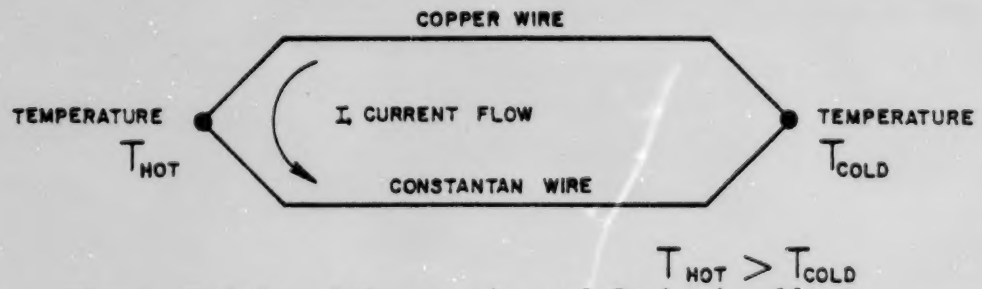


Figure 3-2-1. Illustration of Seebeck effect.

consist of two dissimilar conductors, for example, copper and constantan. (Constantan is a widely used thermocouple wire consisting of 60% copper and 40% nickel.) When the junctions of the conductors are maintained at different temperatures ($T_1 \neq T_2$), an electric current flows continuously. This phenomenon is called the Seebeck effect, a method of converting thermal energy directly to electrical energy. The Seebeck effect cannot be used to produce electricity directly in a steam-electric plant because the voltages produced are in the millivolt range, and efficiencies are much too low.

(In some special applications, however, the Seebeck effect is used to produce electricity, such as for heart pacemakers and for space travel, where low, dependable voltages or currents are all that are required.)

Another phenomenon, similar to the Seebeck effect, is called the Peltier effect (Figure 3-2-2). This effect is observed when an extraneous current flows across the junction of two dissimilar conductors, leading to the absorption or liberation of heat. If current flows in the same direction as current produced by the Seebeck effect in a thermoelectric circuit of two dissimilar conductors, heat is ab-

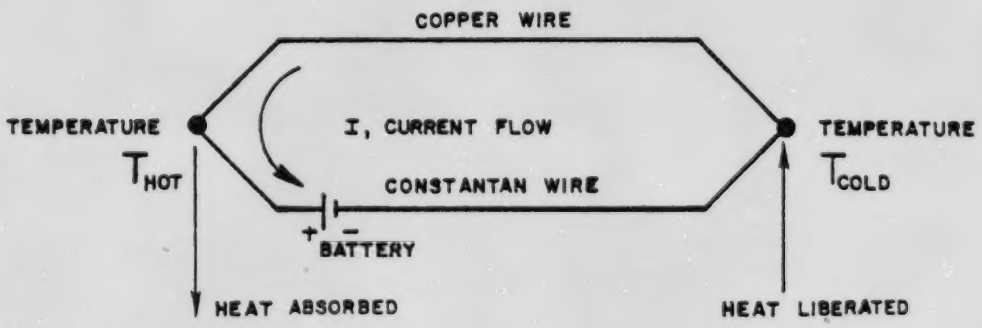


Figure 3-2-2. Illustration of the Peltier effect.

sorbed at the measuring (hot) junction, and heat is liberated at the reference junction. Thus, for example, heat is absorbed at T_{hot} when current flows across a copper-constantan measuring junction from the constantan to the copper.

MEASUREMENT OF THERMOCOUPLE OUTPUT

Output voltage of most thermocouples is in the millivolt range: 1.52 millivolts for a measuring junction at 100°F (37.8°C), with a reference temperature of 32°F (0°C) using a copper-constantan thermocouple. Accurate measurement of this small voltage is dependent upon use of measuring equipment which requires little or zero current for operation.

MILLIVOLTMETER METHOD

This deflection type instrument has a moving coil within the field of a permanent magnet. Current through the coil causes deflection proportional to the current. Voltage measurement is made possible by using a coil with a high input impedance which requires little current for deflection. Thus, the millivoltmeter measures thermocouple voltage but does cause low values of current. Such current causes some voltage loss by the IR loss of the meter leads. Accordingly, leads with low resistance are used. Extremely accurate measurement of thermocouple voltage must consider the voltage drop across the leads: Figure 3-2-3 illustrates the millivoltmeter.

The millivoltmeter is convenient to use, but because of the effects of leads, it may not be of desired accuracy in some applications.

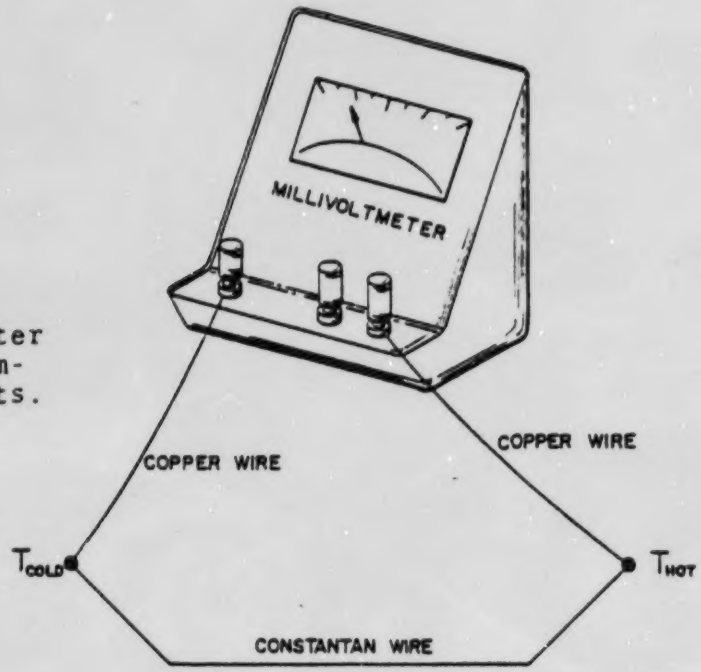


Figure 3-2-3. Typical millivoltmeter connections for temperature measurements.

POTENTIOMETER METHOD

Thermocouple emf or voltage can be balanced against a known emf source (Figure 3-2-4). When the circuit is

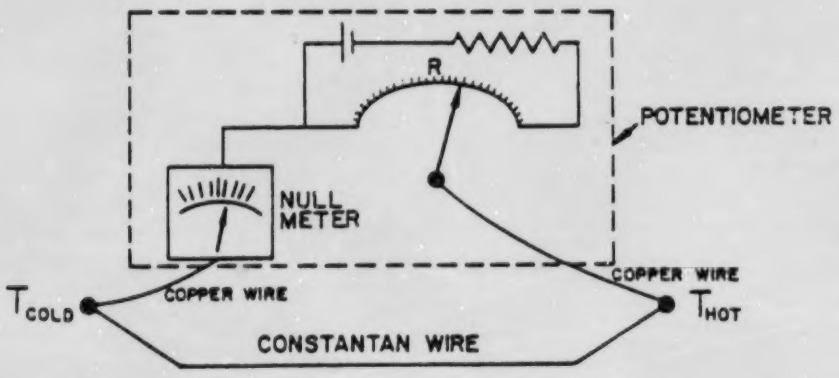


Figure 3-2-4. Potentiometer balancing.

balanced, no current flows. Hence, resistance of leads and connectors does not affect readings.

Operating a null-balancing potentiometer (Figure 3-2-5) requires time and skill. If the sophistication and expense are warranted, however, a motor-operated "automatic" balancer may be used. Electronic null detectors are gaining in importance as devices for measurement and control circuits.

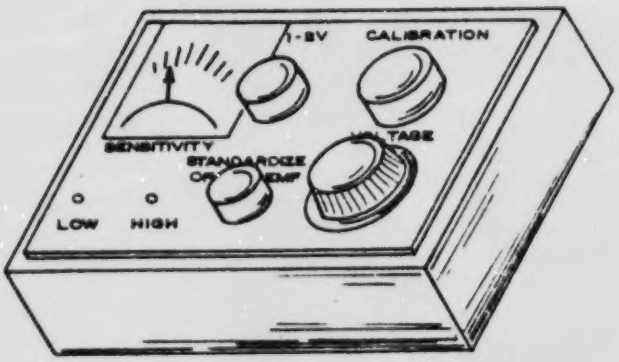


Figure 3-2-5.
Typical null-balancing potentiometer.

MEASUREMENT REFINEMENTS

Typical thermocouple circuits have several refinements beyond the simple millivoltmeter and potentiometer devices discussed in the previous section. For example, a standard voltage cell is included for calibration, and a cold-junction compensator is provided for those instances when unlike wires of the thermocouple are connected directly to binding posts of the instrument.

STANDARD CELL

A standard cell is any special electric cell capable of producing a particular voltage whose value is stable under a given set of reproducible conditions. A standard voltage cell is usually added to the simple circuit shown in Figure 3-2-4 to compensate for voltage changes in the working battery, B.

The best known of several standard cells is a chemical battery called the Weston cell, which has an output at 20°C (68°F) of 1.019 volt. Solid-state power supplies that deliver a very stable direct current output are often used in place of standard cells.

REFERENCE-JUNCTION COMPENSATION

The need for maintaining a known and fixed value of reference-junction temperature, or a reference-junction compensation for its changes, will ultimately depend on the accuracy required in the measurements being made. This accuracy, in turn, depends upon 1) deviation of the reference-junction temperature from the calibrated value (i.e., the reference-junction temperature at which the system is supposed to produce correct measurements) and 2) the difference between reference-junction temperature and measured temperature.

For accurate temperature measurements, particularly those carried out in a laboratory or for an important experiment, the temperature of melting ice, 32°F, is frequently used as a reference standard. Such a temperature is easy to maintain by simply immersing an insulated reference junction into a container filled with cracked ice and water. Such a system, of course, is not practical for many perma-

nent installations, so other methods are used to reduce or eliminate error caused by reference-junction temperature variations.

Most common methods merely "compensate" for changes in reference-junction temperature, rather than attempting to maintain a fixed value of temperature. Some instruments incorporate a compensating device in the form of a bimetallic strip that acts in conjunction with the spiral hairspring of the instrument, varying the tension on the pointer, depending on whether the reference-junction temperature is above or below its correct value.

Another way to compensate for reference temperature is to use a temperature-sensitive resistor in the measuring circuit. This resistor is located close to the reference junction so that both are equally affected by any change in ambient temperature.

THERMOCOUPLE WIRES

Thermocouples may be made of any one of many materials as long as the two conductors are dissimilar. Factors to be considered in selecting a thermocouple for a particular use include:

Temperature range.

Temperature-emf relationship.

Environmental effects on thermoelectric and mechanical properties (including radiation and temperature effects).

Chemical stability and property behavior.

Stability and reproducibility.
Cost.

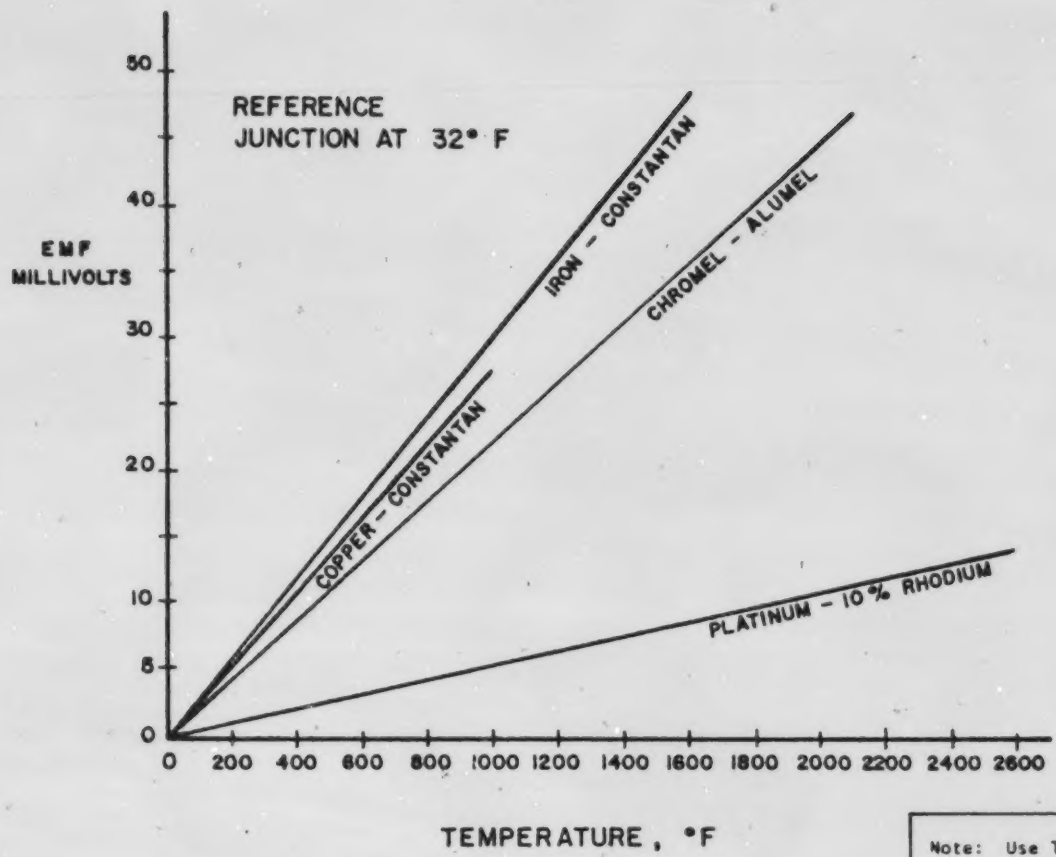
Thermocouple choice depends mostly upon the temperature range in which it is used. Table 3-2-1 indicates the approximate temperature ranges of four of the most common thermocouple types. This table also provides an average accuracy and recommended range for each type.

TABLE 3-2-1
CHARACTERISTICS OF COMMON THERMOCOUPLES

Thermocouple Wires	Practical Temperature Range, °F	Average Accuracy ± of Standard Calibration	Recommended Usage
Copper-Constantan	-300 to 700	3/4%	Low temperature work. Mildly oxidizing and reducing temperatures when moisture is present.
Iron-Constantan	0 to 1400	1%	In reducing atmospheres for general usage.
Chromel-Alumel	0 to 2300	3/4%	Clean, oxidizing atmospheres.
Platinum-Rhodium	0 to 2700	1/2%	In highly oxidizing or corrosive atmosphere.

In the relationship between emf and temperature (Figure 3-2-6) the greater the slope, the greater the precision.

Iron-constantan thermocouples have the advantage of low cost, high emf output and wide range. Hence, they are very common in nonoxidizing atmospheres up to 1500°F (815°C).



Note: Use Table 3-2-2 for more exact values.

Figure 3-2-6. Temperature range applicability and behavior for four different thermocouple combinations.

Copper-constantan allows a simpler circuit because all the wires may be copper except one lead from the hot-to-cold junction, which is constantan. (See section on Measurement Refinements, in which lead wire considerations are discussed.)

Chromel-alumel is generally preferred in the 1500 to 2300°F range. (Chromel is ~ 90% nickel and ~ 10% chromium; alumel is ~ 95% nickel and ~ 5% aluminum, manganese and silicon.)

Platinum-rhodium thermocouples - generally used as basic calibration standards - are more reliable than the others because of freedom from corrosion and high constancy of calibration. But these thermocouples are expensive, and they require more sensitive instruments because they generate smaller emf.

The temperature-emf relationships (Figure 3-2-6) are also given in Table 3-2-2, which allows temperatures to be determined directly from millivoltmeter readings.

EXAMPLE

Given: A chromel-alumel thermocouple, immersed in a hot-air stream, reading 2.28 mV (using a potentiometer), and a reference junction placed in a 32°F ice bath.

Find: Temperature of air stream.

Solution: (From Table 3-2-2) a temperature of 130°F, which gives an emf reading of 2.25 mV, and 140°F, which gives an emf reading of 2.43 mV, both using a 32°F ice bath.

Interpolating,

$$\frac{2.28 - 2.20}{2.43 - 2.20} = \frac{T - 130}{140 - 130}$$

where T = temperature corresponding to 2.28 mV.

Solving for T,

$$T - 130 = (140 - 130) \times \frac{0.08}{0.23}$$

TABLE 3-2-2

TEMPERATURE-emf RELATIONSHIPS
FOR FOUR THERMOCOUPLE PAIRS

°F (32° cold junction)	Copper + constantan - (mV)	Iron + constantan - (mV)	Chromel + alumel - (mV)	Platinum + 10% rhodium - (mV)
40	0.17	0.23	0.18	0.024
50	0.39	0.51	0.40	0.055
60	0.61	0.80	0.62	0.087
70	0.83	1.09	0.84	0.120
80	1.06	1.37	1.06	0.153
90	1.29	1.66	1.29	0.187
100	1.52	1.95	1.52	0.221
110	1.75	2.25	1.74	0.256
120	1.99	2.54	1.97	0.291
130	2.23	2.84	2.20	0.327
140	2.47	3.14	2.43	0.364
150	2.71	3.44	2.66	0.401
160	2.96	3.74	2.89	0.439
170	3.21	4.04	3.12	0.477
180	3.46	4.34	3.36	0.516
190	3.71	4.65	3.59	0.555
200	3.97	4.95	3.82	0.595
210	4.22	5.25	4.05	0.635
220	4.48	5.55	4.28	0.676
230	4.75	5.85	4.54	0.717
240	5.01	6.15	4.74	0.758
250	5.28	6.45	4.97	0.800
275	5.95	7.20	5.53	0.907
300	6.64	7.95	6.09	1.016
325	7.35	8.71	6.64	1.127
350	8.06	9.48	7.20	1.241
400	9.52	11.03	8.31	1.473
500	12.57	14.11	10.56	1.956
600	15.77	17.18	12.85	2.457
700	19.09	20.25	15.18	2.977
800	.....	23.32	17.52	3.505
1000	.....	29.53	22.25	4.594
1200	.....	36.04	26.98	5.725
1400	.....	42.98	31.65	6.898
1600	.....	50.10	36.20	8.110
1800	.....	57.10	40.62	9.365
2000	.....	.....	44.90	10.660
2500	.....	.....	54.87	13.968
3000	.....	.....	.....	17.290

NOTE: Approximation with instruments compensated to 0° cold junction: for a given millivolt reading, find the temperature from this table, then subtract 32°.

= 10 x 0.35

= 3.50

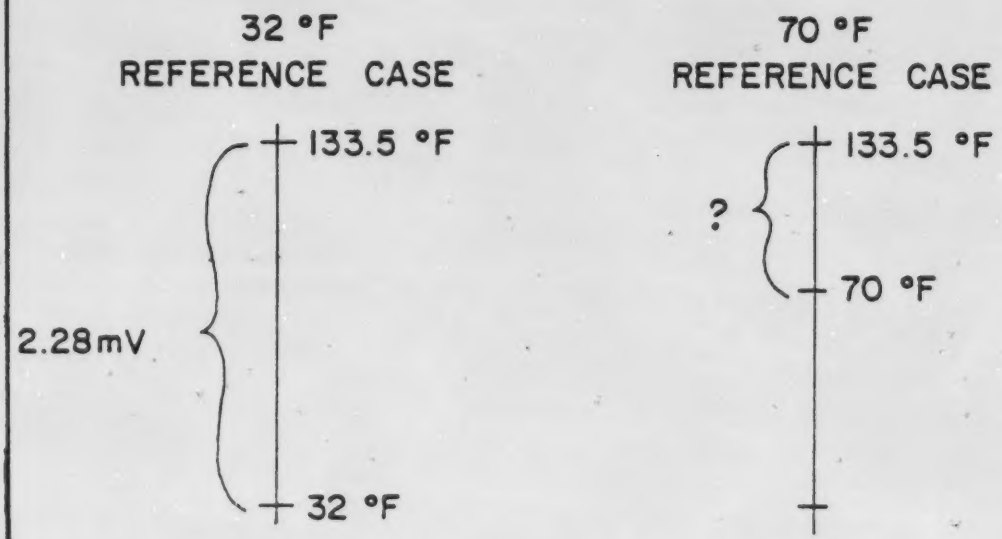
therefore T = 133.5°F.

EXAMPLE

Given: In the previous example, the reference junction was known to be at 70.0°F.

Find: New potentiometer reading.

Solution: The cold junction temperature has been increased to 38°F; the emf has been decreased for the same hot junction temperature as shown schematically below:



To find emf, subtract emf for 70°F (Table 3-2-2) from that at 133.5°F (2.28 mV):

emf = 2.28 mV - 0.84
= 1.64 mV (new potentiometer reading).

EXAMPLE

Given: A hot junction placed in hot water at 200°F; the cold junction at 100°F; the wires are iron and constantan.

Find: Millivoltmeter reading.

Solution: (From Table 3-2-2):

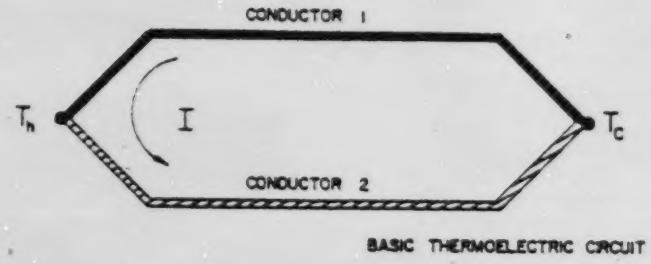
emf between 200°F and 32°F = 4.95 mV.
emf between 100°F and 32°F = 1.95 mV.
emf between 200°F and 100°F = 3.00 mV.

INTERMEDIATE CONDUCTORS AND TEMPERATURES

An important physical law, the Law of Intermediate Conductors (Figure 3-2-7), greatly increases the utility of thermocouples:

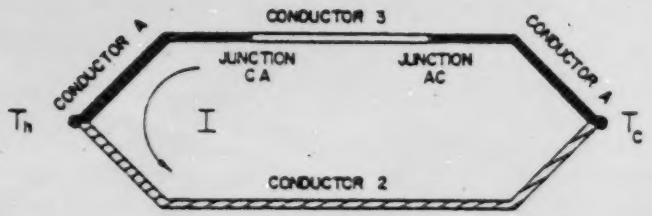
> The net emf in a circuit is unaltered if a third conductor is introduced, provided the two junctions between the new conductor and the circuit are at the same temperature.

The same circuit is shown in A and B, but with a portion of conductor A using a different material. The resulting current



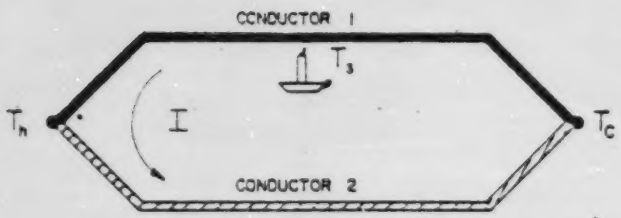
BASIC THERMOELECTRIC CIRCUIT

A. Basic thermoelectric circuit.



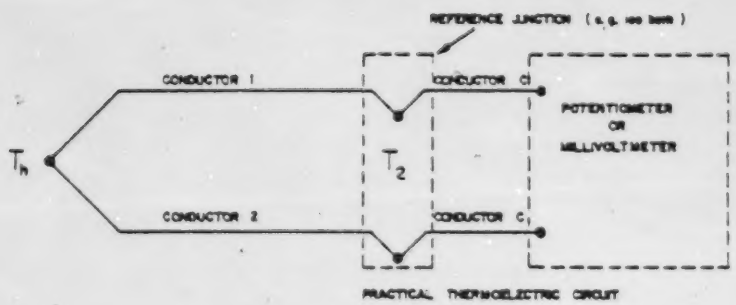
THERMOELECTRIC CIRCUIT WITH THIRD WIRE

B. Thermoelectric circuit with third wire.



THERMOELECTRIC CIRCUIT WITH HEATED WIRE

C. Thermoelectric circuit with heated wire.



PRACTICAL THERMOELECTRIC CIRCUIT

D. Practical thermoelectric circuit.

Figure 3-2-7. Schematic of the applicability of the Law of Intermediate Conductors.

is the same in both cases, because the emf's generated at junctions AC and CA cancel out (if they are at the same temperature).

The significance of this law is that inexpensive lead/extension wires can be used between the junctions without affecting the results, which is important for long lead wires. Also, wires inside the measuring device (e.g., galvanometer) can be of any material as long as the inside junctions are at the same temperature.

In C, the effect of heating a wire along its length to any arbitrary temperature, T_3, demonstrates the Law of Intermediate Temperatures, which states:

> ... current is not affected by the temperature along the wires, but only at the junctions.

A practical circuit for thermocouple voltage measurements, where lead wires are used from the reference junction to the potentiometer, is illustrated in D.

Another important physical law - the Law of Homogeneous Circuits - states:

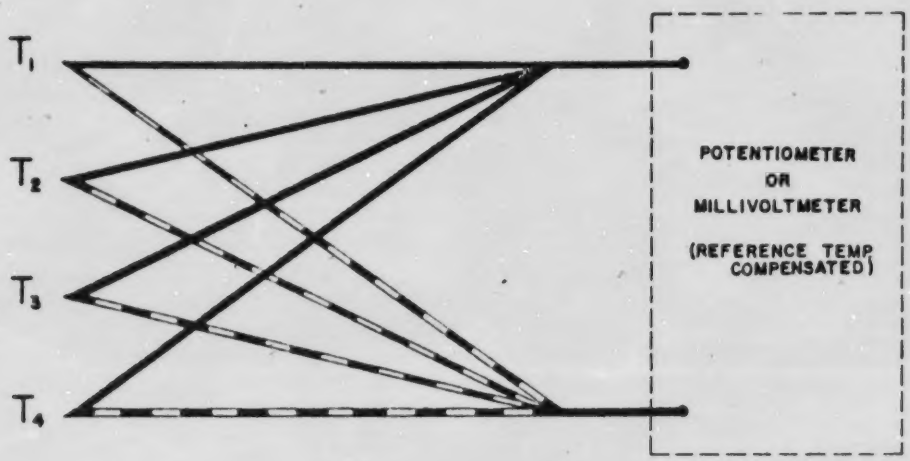
> ... an electric current cannot be sustained in a circuit of a single homogeneous metal by application of heat alone, no matter how the metal may vary in cross section.

Combining the three laws discussed in this section evidences that the emf generated in a thermocouple circuit containing homogeneous conductors is a function only of the temperature of the junctions.

PARALLEL AND SERIES CIRCUITS

The average temperature from several thermocouples

can be obtained by connecting them in parallel (Figure 3-2-8). The resistance of all thermocouples must be the same.



$$emf_{avg} = \frac{E_1 + E_2 + E_3 + E_4}{4}$$

and the average temperature is given by

$$T_{avg} = \frac{T_1 + T_2 + T_3 + T_4}{4} .$$

Figure 3-2-8. Temperature averaging with multiple thermocouples.

If any number of thermocouples of the same type wires are connected in series (Figure 3-2-9) and each subjected to temperature, T_h, at the measuring junction and T_c at the reference junction, the total emf produced is equal to the sum of the emf's of each thermocouple N times the emf of a single thermocouple, where N is the number of thermocouples. This circuit, called a thermopile, enables detection of small changes in temperature.

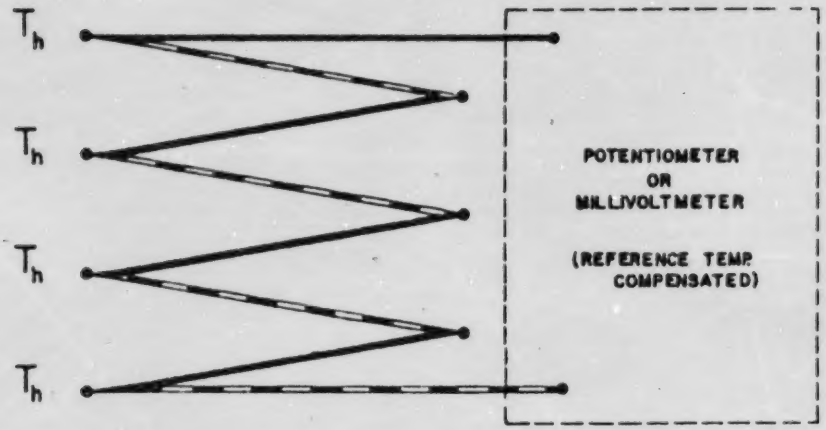


Figure 3-2-9. Thermopile circuit.

GENERAL CONSTRUCTION

Every thermocouple is composed of two essential parts: 1) a pair of joined dissimilar conductors and 2) dielectric insulation to isolate them electrically.

The simplest form of sensor consists of two dissimilar wires welded at one end and electrically insulated. These thermocouples are inexpensive, quick-responding, and easily formed by trained technicians; however, they are also fragile, difficult to mount and susceptible to corrosion.

For most industrial applications, thermocouples must be rugged and corrosion resistant; therefore, they are usually inserted within a protective sheath (Figure 3-2-10), which may be of a metal or refractory material. An exposed junction is used whenever response time must be minimal.

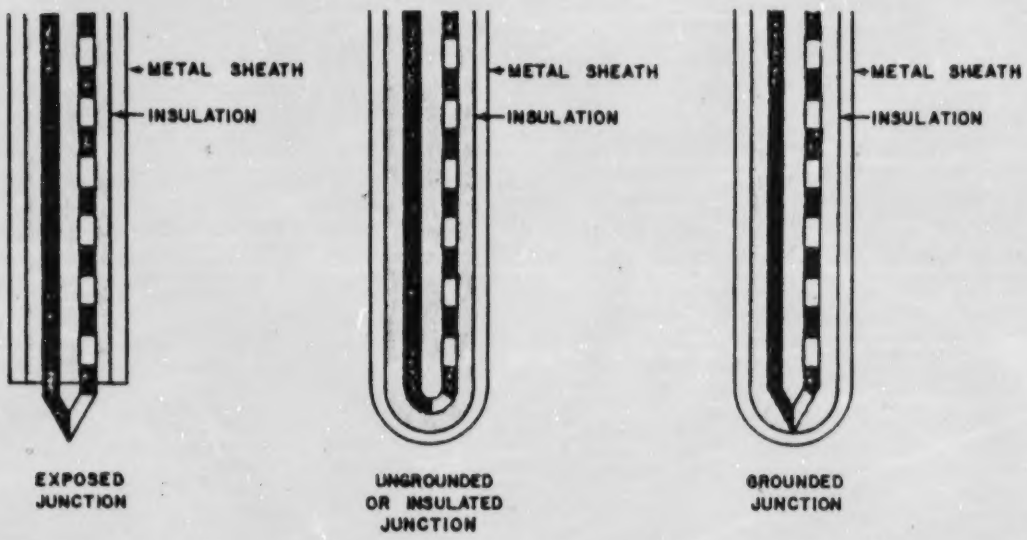


Figure 3-2-10. Types of thermocouple sheaths.

In the grounded thermocouple, the thermocouple junction is physically touching the metal sheath to give faster response and better heat conduction; however, errors may arise from unwanted, external voltage sources. The insulated or ungrounded junction thermocouple eliminates errors caused by external voltages.

Thermocouple wires may be of any thickness - the thickness has no bearing on the emf generated for a given junction temperature. Smaller diameter wires give a quicker response to temperature changes, however, because of reduced thermal inertia. Thicker wires have longer life but alter the rate at which heat is conducted away from the junction, which may cause the junction to be at a temperature significantly different from that intended, or measured (a temporal lag).

A corresponding emf will be generated by any form of junction, provided electrical contact is made between the two thermocouple metals, whether or not contact is through an intermediate metal. Junctions are usually made by brazing or welding, though some applications may demand special techniques.

GENERAL APPLICATION RULES

THERMOCOUPLES

1. Select thermocouple location to avoid stagnant areas of measured medium. Area selected must be representative of mass of medium. When necessary, insert several thermocouples and take parallel readings to obtain average temperature.
2. Avoid direct flame impingement on thermocouple or protecting tube. Flame impingement generally shortens tube or element life and certainly does not reflect a representative temperature.
3. Provide for sufficient depth of immersion of thermocouple into measured medium to minimize heat transfer along protecting tube to connection head. Heat conducted away from tip of measuring junction causes thermocouple to indicate a lower temperature. Recommended minimum immersion is approximately ten times outside diameter of tube.
4. When measuring high temperatures, install thermocouple in vertical position to prevent protecting tube from sagging.

EXTENSION (LEAD) WIRE

1. Use only proper type of extension wire for given type of thermocouple.
2. Select proper insulation to meet conditions of its environment.
3. Observe color coding of individual conductors; connect red (negative) wire to negative terminal at thermocouple connection head and instrument.
4. When possible, avoid splicing of wire; if necessary, however, use silver solder and tape or sleeve to avoid shorting or grounding at splice.
5. Install extension wires in conduit, wherever possible, and ground conduit to prevent leakage from power or lighting circuits.
6. Do not run wires parallel to or across any electrical lines within a distance of one foot. Induced a.c. currents may affect temperature readings. Never run electrical power wires in same conduit with thermocouple extension wire.

MAINTENANCE HINTS

1. Check thermocouples regularly. Intervals must be determined largely by experience, but once a month is usually sufficient, or when suspicious readings are obtained. Confidence in instrumentation is essential.
2. If thermocouple is removed, reinsert replacement to same depth.
3. Replace burned out protection tubes promptly to avoid damage to thermocouples.
4. Check out extension wire circuits; remove instrument and thermocouple connections and test insulation resistance.

5. If instruments are connected for parallel operation from a thermocouple, check carefully for affect of one instrument on the other.

EXERCISES

1. A technician is given the job of connecting a thermocouple; the millivoltmeter method is used (Figure 3-2-11), and a choice of No. 16 or No. 22 copper lead wires is given. For minimum error, which size wire should be used? Explain the answer.

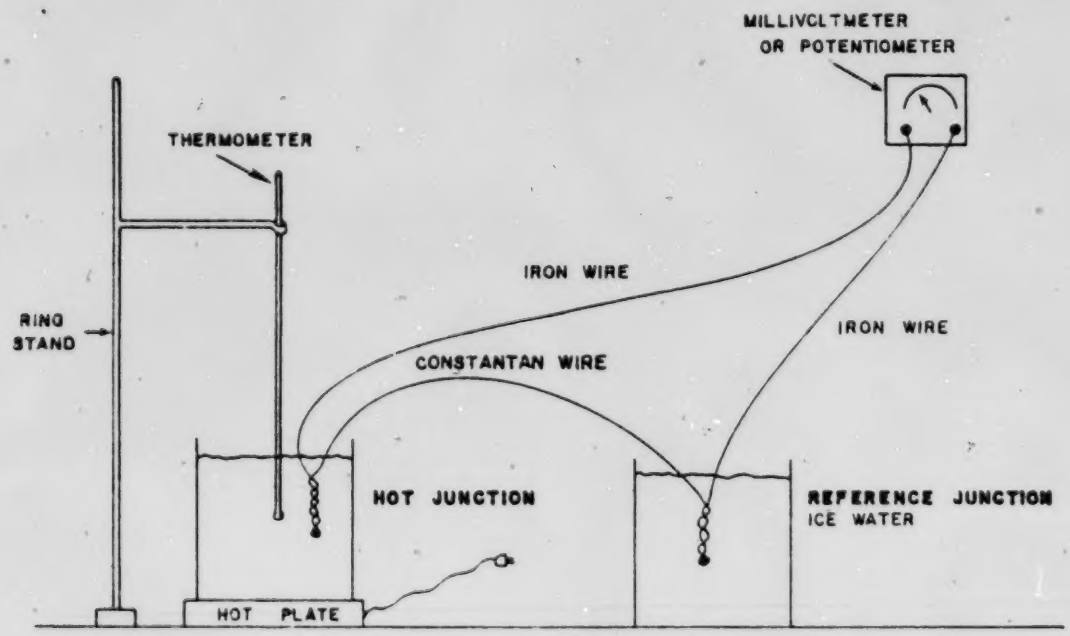


Figure 3-2-11. Experimental arrangement for millivoltmeter method.

2. Would the answer change if the technician used a potentiometer instead of a millivoltmeter? Explain the answer.

3. A technician is given the job of using a copper-constantan thermocouple to read a water temperature of about 600°F. The reference junction is to be placed in a bath known to be exactly 148.2°F. What will be the approximate reading on the millivoltmeter?

MATERIALS

1 Millivoltmeter (0-50 mV).
1 Dial-type potentiometer with builtin standard cell.
10 Feet iron-constantan thermocouple wire.
1 Hot plate.
3 Beakers.
5 Ring stands.
2 Thermometers, 0-230°F, 2°F subdivisions.
2 Thermometers, -20°-110°C, 1°C subdivisions.
1 Temperature recorder.
Cracked ice.
10 Feet copper lead wire.

PROCEDURES

MILLIVOLTMETER METHOD

1. Set up an iron-constantan thermocouple as shown in Figure 3-2-11.
2. Heat water to boiling; take reading on thermometer and on millivoltmeter; record results on Data Table 3-2-1.
3. Remove hot water from hot plate; as water cools, take millivoltmeter readings at 10°F intervals (measured by the thermometer) until water temperature reaches 32°F. To hasten cooling, and to reduce temperature below room temperature, add ice to water and stir mixture to ensure equilibrium conditions.
4. From Table 3-2-1 (for iron-constantan thermocouple), record expected emf for each temperature; use Data Table 3-2-1.
5. Plot (on graph paper) temperature versus observed and expected emf; use Data Table 3-2-1.
6. In the space provided in Data Table 3-2-1, explain any difference in two curves on graph.

POTENTIOMETER METHOD

Note: If potentiometer has a reference-junction compensation, an ice bath will not be required.

1. Repeat procedure from Millivoltmeter Method (above), but use potentiometer instead of a millivoltmeter. Follow instructions (given in operations manual or by instructor) for operating potentiometer.

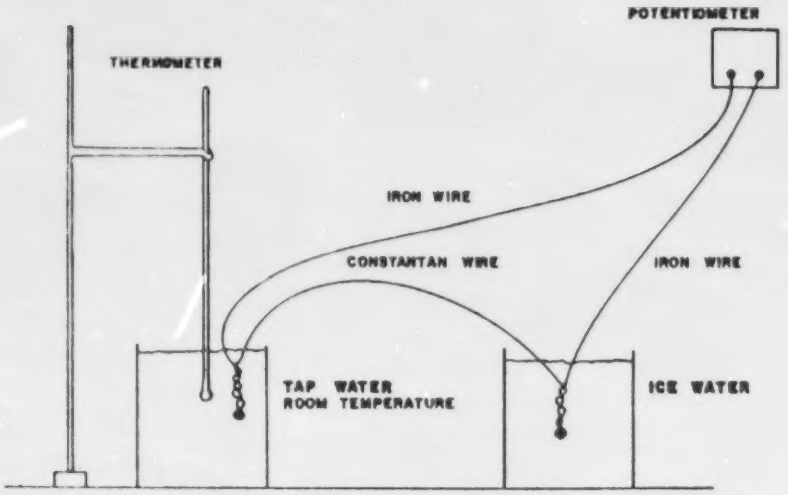
2. Record results on Data Table 3-2-2; plot results on graph used above.
3. From data on Data Table 3-2-2, explain relative merits of millivoltmeter and potentiometer methods.

INTERMEDIATE CONDUCTORS AND TEMPERATURES

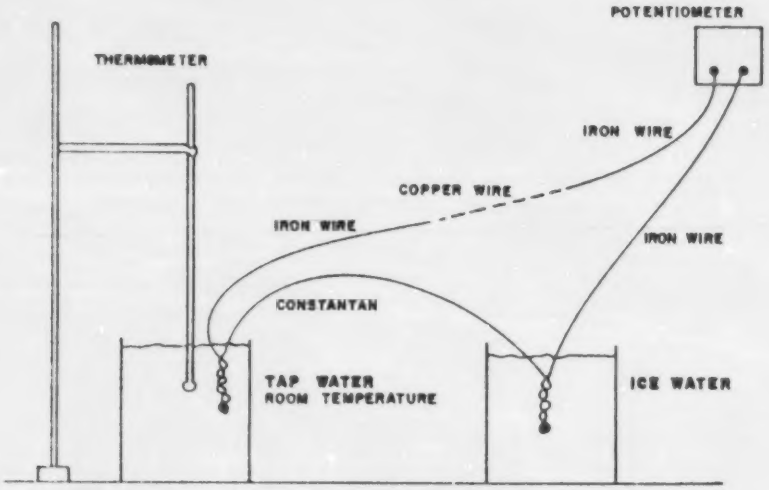
The purpose of this procedure is to verify the Laws of Intermediate Conductors and Intermediate Temperatures.

1. Use potentiometer; set up a thermocouple as shown in Figure 3-2-12A; use tap water at room temperature.
2. Record potentiometer and thermometer readings on Data Table 3-2-3.
3. Cut iron wire at midpoint and connect copper wire as shown in Figure 3-2-12B. Do not change water temperature.
4. Record potentiometer and thermocouple readings on Data Table 3-2-3.
5. Is there a difference in potentiometer reading with the copper wire in place? Explain results.
6. Set up thermocouple as shown in Figure 3-2-12C, with part of one wire in a beaker of boiling water.
7. Record potentiometer and thermocouple readings on Data Table 3-2-3.
8. Does it make any difference if one thermocouple wire is heated in the middle? Explain the results.

A



B



C

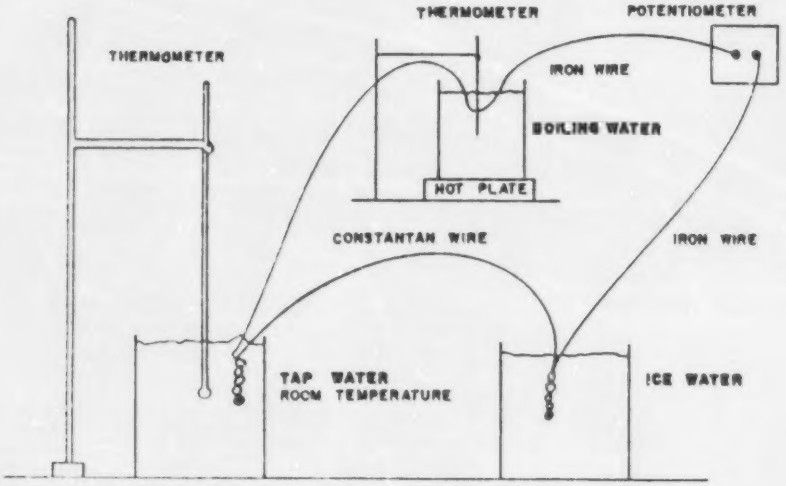


Figure 3-2-12. Thermocouple temperature measurements and arrangements.

PARALLEL AND SERIES CIRCUITS

1. Connect two thermocouples in parallel as shown in Figure 3-2-13; use both tap water at room temperature and boiling water.

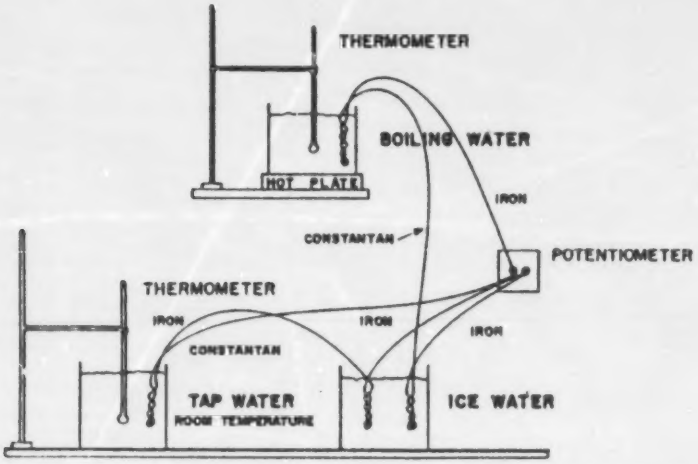


Figure 3-2-13. Experimental arrangement to verify Law of Intermediate Conductors.

2. Does temperature from thermocouples in parallel agree with average thermometer temperature? Explain significance of this result on Data Table 3-2-4.
3. Connect two thermocouples in series as shown in Figure 3-2-14; use tap water at room temperature.
4. Record potentiometer and thermometer readings on Data Table 3-2-4.
5. From Table 3-2-1, obtain temperature corresponding to one-half of potentiometer reading.
6. Does this temperature agree with thermometer reading?
7. Why is it sometimes desirable to connect thermocouples in series?

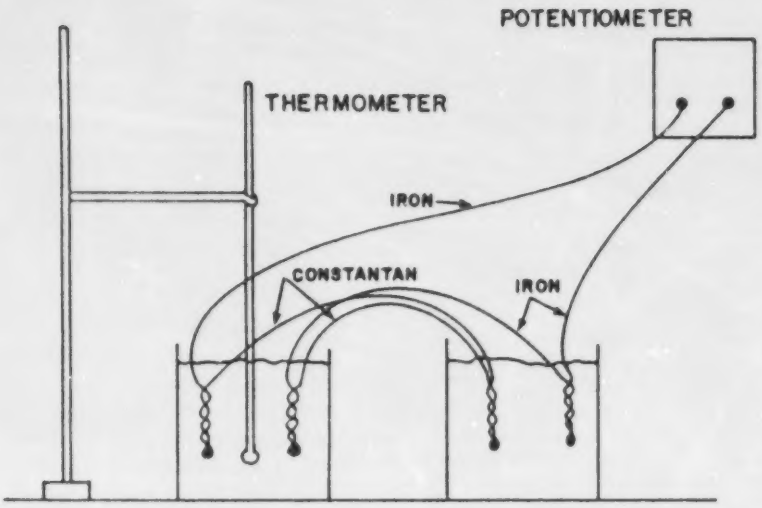


Figure 3-2-14. Additional arrangement for verifying the Law of Intermediate Conductors (thermopile).

TEMPERATURE RECORDER CALIBRATION

1. Follow instructor's directions to zero recorder; use a standard cell.
2. Use a hot plate to vary water temperature; use centigrade-graduated thermometer to take readings of approximately 20°C increments; record results on Data Table 3-2-5.
3. Plot results on graph paper.
4. Find location of standard cell and reference-junction compensation in recorder; point them out to instructor.
5. Explain, on Data Table 3-2-5, how standard cell was used.

LABORATORY DEMONSTRATION

The instructor will demonstrate the following accessories:

1. Exposed junction sheath.
2. Grounded junction sheath.
3. Ungrounded junction sheath.
4. Quick-disconnect assembly.
5. Unsheathed fine-gage thermocouple.
6. A variety of thermowells.
7. Compression fittings.
8. Connectors and adapters.

The student will then identify each of these accessories and give its purpose.

DATA TABLE 3-2-1

MILLIVOLTMETER METHOD

Type thermocouple materials _____

Reference junction, °F _____

Hot Junction Temperature, °F	Observed Millivoltmeter Reading, mV	Expected emf, from Table
212°F		
200		
190		
180		
170		
160		
150		
140		
130		
120		
110		
100		
90		
80		
70		
60		
50		
40		
32		

Explain difference between the two curves on the graph (from observed and expected emf's).

DATA TABLE 3-2-2

POTENTIOMETER METHOD

Type thermocouple materials _____

Reference junction, °F _____

Hot Junction Temperature, °F	Observed Potentiometer Reading, mV
212°F	
200	
190	
180	
170	
160	
150	
140	
130	
120	
110	
100	
90	
80	
70	
60	
50	
40	
32	

Explain the relative merits of the millivoltmeter and potentiometer methods.

DATA TABLE 3-2-3

INTERMEDIATE CONDUCTORS AND TEMPERATURES

	Thermometer °F (in tap water)	Potentiometer, mV
1. Basic thermocouple setup (Figure 3-2-12A)		
2. Third (copper) wire in place (Figure 3-2-12B)		
3. Wire in boiling water (Figure 3-2-12C)		

4. Does it make any difference in the potentiometer readings (between parts 1 and 2 above) with the third wire in place?

5. Does it make any difference in the potentiometer readings (between parts 1 and 3 above) with one of the thermocouple wires heated in the middle?

DATA TABLE 3-2-4
PARALLEL AND SERIES CIRCUITS

A. Parallel circuits:

1. Thermometer readings -

   Tap water _____°F

   Boiling water _____°F

   Average of both tap and boiling water temperatures _____°F

2. Thermocouple readings in parallel -

   Potentiometer reading _____mV

   Temperature from Table 3-2-1 corresponding to potentiometer reading _____°F

3. Does the temperature from the thermocouples in parallel agree with the average thermometer temperatures? Explain the significance of this result.

B. Series circuits:

1. Thermometer reading _____°F
2. Potentiometer reading _____mV
3. One-half of potentiometer reading _____mV
4. Temperature from Table 3-2-1 corresponding to one-half of potentiometer reading _____°F
5. Do the temperatures from parts 1 and 4 agree? Explain any significant difference.

6. Explain why it is sometimes desirable to connect thermocouples in series.

DATA TABLE 3-2-5
TEMPERATURE RECORDER CALIBRATION

Type thermocouple materials _____

Temperature from Thermometer, °C	Temperature Reading from Chart, °C

Explain how the standard cell was used in this temperature calibration.

Bass, H.G. Introduction to Engineering Measurements. New York: McGraw-Hill, 1975.

Harris, Norman C. Experiments in Applied Physics. 2nd ed. New York: McGraw-Hill, 1972.

Kinzie, P.A. Thermocouple Temperature Measurement. New York: John Wiley & Sons, 1973.

Paul Trinity Micro Corporation. Thermocouple Guidebook, Bulletin TT-335. Costland, NY: Paul Trinity Micro Corp.

TEST

Read each question carefully. Be sure your responses give the specific information each question requires. Your answers should be brief. Use the backs of the test if you need more space.

1. Temperature is not measured directly, but rather by its effects. List four types of effects that are measured and used to determine temperature.

   a. _____

   b. _____

   c. _____

   d. _____

2. What are two reasons a thermocouple has a wider useful range and broader application than any other temperature sensing device?

   _____

   _____

3. Basically, a thermocouple is a transducer that converts one form of energy into another. What type of energy is converted? Into what type of energy is it converted?

   _____

4. Two phenomena that govern the behavior of a thermocouple are the Seebeck Effect and the Peltier Effect. Briefly explain these effects.

   _____

   _____

   _____

   _____

   _____

   _____

   _____

   _____

   _____

   _____

5. Answer these questions about the millivoltmeter method of measuring output voltage of a thermocouple:

   a. The millivoltmeter is made with a permanent magnet and a moving coil. What happens to the coil when a voltage is applied across it?

   _____

   b. From what source does the millivoltmeter use the voltage to activate meter mechanism?

   _____

   c. What is one factor that can affect the accuracy of the millivoltmeter?

   _____

6. Answer these questions about the potentiometer:

   a. How does the potentiometer measure voltage?

   _____

   _____

   _____

   b. What is a standard cell? Why is it frequently necessary to use a standard cell with a potentiometer?

   _____

   _____

   _____

   _____

   _____

   _____

   c. What is a null-balancing potentiometer?

   _____

   _____

   _____

   _____

   _____

7. In using a thermocouple, why is it important to control reference-junction temperature variation? What is one common method of compensating for changes in reference-junction t mperature?

8. List six factors to be considered in selecting a thermocouple for a particular use.

   a. _____

   b. _____

   c. _____

   d. _____

   e. _____

   f. _____

9. Name two metals that are used together for thermocouple wires. Describe the atmospheric condition and temperature range for which a thermocouple that uses these metals would be recommended.

10. The Law of Intermediate Conductor (Metals) greatly increases the utility of thermocouples in industry. What does this law state? Why does it increase the use of thermocouples?

11. What is a thermopile?

12. Briefly explain why it is possible to have a thermopile circuit that can detect small changes in temperature.

13. Why is a thermocouple inserted into a sheath?

14. What is the difference between a grounded and an ungrounded thermocouple? Which would be most likely to have errors?

15. Given an iron-constantan thermocouple immersed in a hot air stream, reading 4.10 mV and a reference junction placed in a 32°F ice bath, calculate the temperature of air stream. (Use the enclosed table Temperature-emf Relationship for Four Thermocouple Pairs.)

16. Given a chromel - alumel thermocouple immersed in a hot air stream, reading 2.66 mV and a reference junction placed in a 32°F ice bath, find the temperature of the air stream. (Use the same table as for Problem 15.)

17. Given platinum - rhodium wires with a hot junction placed in hot water at 250°F and the cold junction at 110°, find the millivoltmeter reading. (Use the same table as for Problems 15 and 16.)

TABLE 3-2-2

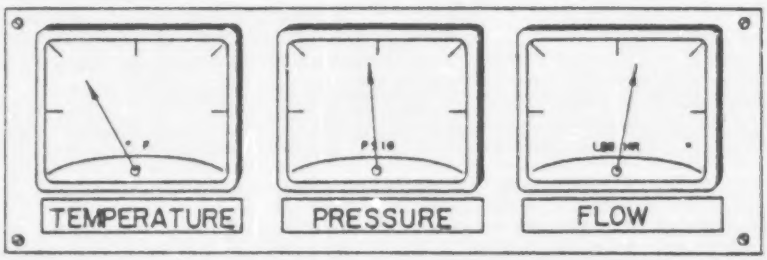
TEMPERATURE-emf RELATIONSHIPS
FOR FOUR THERMOCOUPLE PAIRS

°F (32° cold junction)	Copper + constantan - (mV)	Iron + constantan - (mV)	Chromel + alumel - (mV)	Platinum + 10% rhodium - (mV)
40	0.17	0.23	0.18	0.024
50	0.39	0.51	0.40	0.055
60	0.61	0.80	0.62	0.087
70	0.83	1.09	0.84	0.120
80	1.06	1.37	1.06	0.153
90	1.29	1.66	1.29	0.187
100	1.52	1.95	1.52	0.221
110	1.75	2.25	1.74	0.256
120	1.99	2.54	1.97	0.291
130	2.23	2.84	2.20	0.327
140	2.47	3.14	2.43	0.364
150	2.71	3.44	2.66	0.401
160	2.96	3.74	2.89	0.439
170	3.21	4.04	3.12	0.477
180	3.46	4.34	3.36	0.516
190	3.71	4.65	3.59	0.555
200	3.97	4.95	3.82	0.595
210	4.22	5.25	4.05	0.635
220	4.48	5.55	4.28	0.676
230	4.75	5.85	4.54	0.717
240	5.01	6.15	4.74	0.758
250	5.28	6.45	4.97	0.800
275	5.95	7.20	5.53	0.907
300	6.64	7.95	6.09	1.016
325	7.35	8.71	6.64	1.127
350	8.06	9.48	7.20	1.241
400	9.52	11.03	8.31	1.473
500	12.57	14.11	10.56	1.956
600	15.77	17.18	12.85	2.457
700	19.09	20.25	15.18	2.977
800	.....	23.32	17.52	3.505
1000	.....	29.53	22.25	4.594
1200	.....	36.04	26.98	5.725
1400	.....	42.98	31.65	6.898
1600	.....	50.10	36.20	8.110
1800	.....	57.10	40.62	9.365
2000	.....	.....	44.90	10.660
2500	.....	.....	54.87	13.968
3000	.....	.....	.....	17.290

NOTE: Approximation with instruments compensated to 0° cold junction: for a given millivolt reading, find the temperature from this table, then subtract 32°.

NUCLEAR TECHNOLOGY

MODULE 3-3 TEMPERATURE-SENSING DEVICES:
RESISTANCE THERMOMETERS



PRINCIPLES OF
PROCESS INSTRUMENTATION

COURSE 3

COURSE MODULES

COURSE 3 PRINCIPLES OF PROCESS INSTRUMENTATION

MODULE 3-1 Temperature-Sensing Devices: Glass-Bulb Thermometers

MODULE 3-2 Temperature-Sensing Devices: Thermocouples

MODULE 3-3 Temperature-Sensing Devices: Resistance Thermometers

MODULE 3-4 Temperature-Sensing Devices: Pyrometers

MODULE 3-5 Basic Principles of Flow Measurement

MODULE 3-6 Pressure-Sensing Devices

MODULE 3-7 Flow-Sensing Devices: Differential-Pressure Flowmeters

MODULE 3-8 Flow-Sensing Devices: Linear Flowmeters

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INTRODUCTION

In the previous modules of this course, the concept of temperature was discussed along with the fact that temperature, as one of the major process variables, often is not measurable directly. On the other hand, changes in physical properties of a material resulting from a change in its temperature are measurable. For example, volumetric or physical expansion of a column of mercury in a glass-bulb thermometer can be measured. Also the induction of an emf by the bimetal coupling of a thermocouple, an example of a change in physical properties of materials brought about by a temperature change, is measurable.

Another measurable property change, and one that has broad and extensive industrial applications, is the change in a material's electrical resistance as a function of a temperature change. The process instrument used to measure this effect is called a resistance thermometer, or resistance temperature detector (RTD).

This module discusses these resistance thermometers in terms of their principles of operation, materials selection and construction, measuring circuitry, performance characteristics and applications. The advantages and disadvantages, methods of calibration and installation of such thermometers are also detailed.

A comparison of such thermometers to other types of measuring devices is made in terms of basic requirements such as accuracy, range, speed of response and stability. Within the text of the module, the term RTD will be used synonymously with resistance thermometer.

Also, the concept of thermistors is briefly introduced, along with their basic principle of operation and application.

MODULE PREREQUISITES

The student should have successfully completed courses in basic electronics and algebra. Module 3-1, "Temperature Sensing Devices: Glass-Bulb Thermometers," and Module 3-2, "Temperature Sensing Devices: Thermocouples," should have been completed. Previous experience in normal laboratory practices and setting up of electrical measurement equipment is required, together with appropriate electrical laboratory safety appreciation.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms:
   Temperature coefficient of resistance (furnish units).

Thermistor.
Accuracy.
Stability.
Drift.
Response time.
Self-heating effect.
Reproducibility.
Sensitivity.
Platinum resistance thermometer.
Fixed-point ice-bath calibration.
Comparison calibration.

2. Explain basic principles and operation of resistance thermometers; include sign and magnitude of generated signal.
3. Describe basic components of a resistance thermometer.
4. Describe and sketch a basic "three lead-wire circuit" (one-line diagram) as used in measuring instrumentation for resistance thermometers.
5. Explain implications and applicability of different resistance wire material, size and configuration.
6. Identify basic qualities to be considered in the use of a resistance temperature detector, and sources of errors in its misapplication.
7. Predict, from appropriate tables, expected resistance of a particular wire material at a specific temperature.
8. Discuss basic construction, properties and uses of thermistors.
9. Compare resistance thermometers with thermocouples and thermistors (include relative cost, accuracy, ease of operation, response time and simplicity).
10. Identify typical power plant applications of RTD's.

11. Assemble a resistance temperature detector unit: connect to measuring circuit; establish a fixed-point of calibration; measure temperature of fluid; measure response time and calibrate over a major portion of a 0°C - 100°C temperature range.
12. Sketch the basic components of a typical RTD thermowell.
13. Calculate response time of RTD from experimental data.

RESISTANCE TEMPERATURE DEVICES

In Module 3-2, "Temperature Sensing Devices: Thermocouples," the importance of knowing and controlling the temperature of materials, components and systems was emphasized. Equally important to certain nuclear power plant operations and safety is the need for greater accuracy and stability of temperature measuring devices.

Measurement of temperatures, using a change in the characteristic electrical resistance of a material, has been known for over a century; however, only since World War II have significant developments and innovations, resulting from the availability of high-purity metals and accurate electronics, provided this temperature measuring system with sufficient quality for broad and extensive industrial use.

Commercially available resistance thermometers, when interfaced with modern computers or digital process-control systems, have enabled power plants to operate more efficiently and with reduced impact on the environment. For example, the temperatures of cooling water, as it flows through a nuclear power plant, is of key importance in the efficient and safe operation of the plant. These temperatures are monitored by RTD's, which, in turn, may direct the adjustment of control rods in the core. In this manner, optimum temperatures of the coolant may be maintained.

Thermally sensitive resistors formed from complex metallic oxides and other semiconductor materials are also used as resistance thermometers. These process sensors, called thermistors, are similar to resistance thermometers in that a change in their electrical characteristic resistance with temperature can also be used to measure a temperature change. However, the sign, linearity and magnitude of the corresponding resistance change is markedly different from other RTD's, leading to other applications. Thermistors exhibit very large negative changes in resistance for relatively small changes in temperature.

RTD's, which have highly accurate, wide temperature ranges, and compatibility for remote readout, are generally used in control application. Temperatures in the range of -260°C to 820°C are measurable.

Disadvantages of an RTD (compared with a thermocouple) include: 1) more expensive, 2) larger, 3) area sensitivity, 4) tendency to suffer radiation damage (in high-energy neutron and gamma-ray fields), 5) lower maximum temperature limits, 6) susceptible to electrical leakage and 7) requirement for three or four lead wires for high accuracy.

PRINCIPLES OF OPERATION

The principles of operation of the resistance thermometers are not as complex as those of thermocouples. RTD operation is based on the fact that electrical resistance, for most metals, varies in a proportional manner with tem-

perature. This response has been determined, to a high degree of accuracy, to be practically linear over a substantial temperature range. In addition, the resistance change is completely reversible; that is, the metal has the same characteristic after extended use over fairly large temperature cycles.

RESISTANCE THERMOMETRY

The fractional change in electrical resistance of a material per unit change in temperature is the temperature coefficient of resistance for that material. The coefficient and units are expressed as fractional change in resistance (ohms per ohm) per degree of temperature change at a specific temperature.

The value of this coefficient varies with the metal and its purity. For most metals, the temperature coefficient is positive and is about 0.3 to 0.6 percent of the resistance per degree temperature change.

Different metals generally have different coefficients. (Figure 3-3-1). A useful and sensitive resistance thermom-

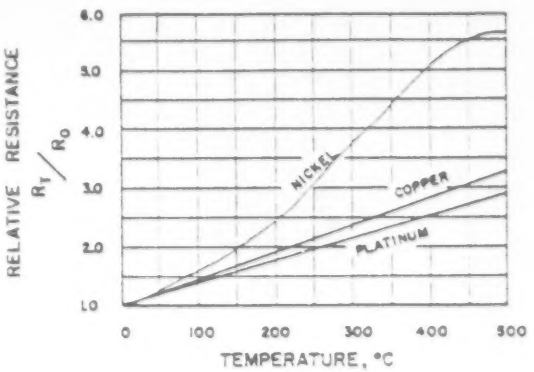


Figure 3-3-1.
Resistance versus temperature for common thermometric materials.

eter requires a metal with a high coefficient of resistance, and electrical resistiviety. For this reason, industrial resistance thermometers (RTD's) are usually made of platinum, copper or nickel.

Relative resistance with respect to 0°C is defined as R_T/R_0. For pure metals, a simple relationship between resistance and temperature can be expressed as follows:

$$R_T = R_0 (1 + \alpha T) \qquad \text{Equation 3-3-1 (Equation = Eq.)}$$

where

R_T = resistance in ohms at temperature T.

R_0 = resistance in ohms at 0°C (or some other reference temperature).

α = temperature coefficient of resistance.

Tables of R_T/R_0 versus temperature relationships are published in various handbooks and by resistance thermometer manufacturers. These tables should be consulted when determining a sensor element's resistance at a specific temperature.

The calculated results of the resistance-temperature relationship for industrial platinum RTD's are given in Table 3-3-1.

OTHER BASIC REQUIREMENTS

Additional basic requirements for a good resistance thermometer's sensor element include:

TABLE 3-3-1

RESISTANCE VERSUS TEMPERATURE
(INDUSTRIAL PLATINUM)

DEGREES C	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100	Ω/° C
0	100.00	96.09	92.16	88.23	84.29	80.32	76.34	72.35	68.34	64.32	60.28	0.397

DEGREES C	0	10	20	30	40	50	60	70	80	90	100	Ω/° C
0	100.00	103.90	107.79	111.67	115.54	119.40	123.24	127.07	130.89	134.70	138.50	0.385
100	138.50	142.29	146.06	149.82	153.57	157.31	161.04	164.76	168.46	172.16	175.83	0.373
200	175.83	179.50	183.16	186.82	190.45	194.07	197.69	201.29	204.88	208.46	212.02	0.362
300	212.02	215.58	219.12	222.66	226.18	229.69	233.19	236.68	240.16	243.61	247.08	0.351
400	247.08	250.52	253.95	257.37	260.77	264.17	267.56	270.94	274.29	277.64	280.98	0.339
500	280.98	284.31	287.63	290.93	294.22	297.50	300.76	304.02	307.27	310.51	313.72	0.327
600	313.72	316.93	320.12	323.31	326.5	329.6	332.8					0.318

(International Practical Temperature Scale, 1968.)

Very pure metal to maintain necessary linearity.
Good thermal conductivity throughout for shortening response time of thermometer.
Minimum of inductance.
Minimum of induced strain when fabricated.
Continued purity while in use (resistance to corrosion).
Sufficient ductility to permit fabrication into uniform cross section.
High melting point.
Nonvolatilization at or below 1000°C.

RESISTANCE MATERIALS

Platinum has the best characteristics for fabrication of sensor elements, and is currently used for most power plant and industrial purposes. It has an acceptable resistivity, a high melting point, is nonoxidizing, is readily available, has a large positive (and quite linear) temperature coefficient resistance, 0.00385Ω/Ω over (0°C) (from 0° - 100°C) (Figure 3-3-1). Though platinum is expensive, only small amounts of it are required.

It is also used as the laboratory reference material for standard resistance thermometers (25.5 Ω at 0°C calibrations, IPTS-68). Platinum elements are normally sized to give a base resistance of 100 ohms at 0°C. As will be emphasized later, this 100 ohms is the nominal base value used by most manufacturers.

Copper is inexpensive, available as a pure metal and has the most linear of all known temperature-resistance relationships. Because it has low electrical resistance, larger sized sensor elements are required. Copper oxidizes readily, but can have a limited useful lifetime if protected. There is a trend toward use of copper in industry; however, the need for high accuracy and reliability of temperature measurements in the nuclear power industry normally dictates use of platinum elements (in preference to copper).

Nickel and tungsten are used in RTD's; however, they are more limited in use than platinum or copper because of the nonlinearity of nickel above 300°C and the lack of a well documented resistance-versus-temperature relationship for tungsten.

DESIGN FEATURES

An industrial resistance temperature detector used in power plants (Figure 3-3-2) is apt to consist of a sensing element of platinum, nickel or copper, internal lead wires, an internal mount and support structure, insulating material and a primary protection tube.

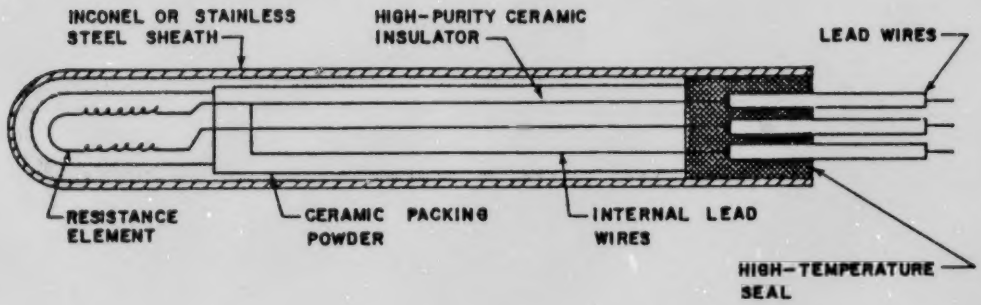


Figure 3-3-2. Typical resistance temperature detector assembly.

The sensor element of an RTD usually consists of a small-diameter wire deliberately cut to a length that gives a preselected resistance at 0°C (normally 10, 25, 100 or 200 ohms). This wire is coiled within a tube or wound on a notched core, which is electrically insulated from its protective sheath or tube. The sensor unit, with its internal lead wires, is packed into a housing, using an insulating ceramic (such as aluminum oxide) of a very high purity, usually at least 99.7%.

A hermetic seal of epoxy may be provided where the external lead wires exit the sensor housing.

Extension fittings are frequently used to reduce ambient temperature at the sensor connection to below 200°C.

Resistance temperature detectors are designed principally for installation in thermowells, or for direct immersion through pipe or vessel walls. Those RTD's to be directly immersed in corrosive liquids or vapors have an outer (secondary) protective sheath of Inconel or some other suitable material.

Where high temperature, high pressure, high flow or vibration make up the environment, an RTD is generally inserted into thermowell protecting tubes. These tubes allow removal of the RTD without interrupting or shutting down a process. The thermowell also serves as a second protective sheath (Figure 3-3-3).

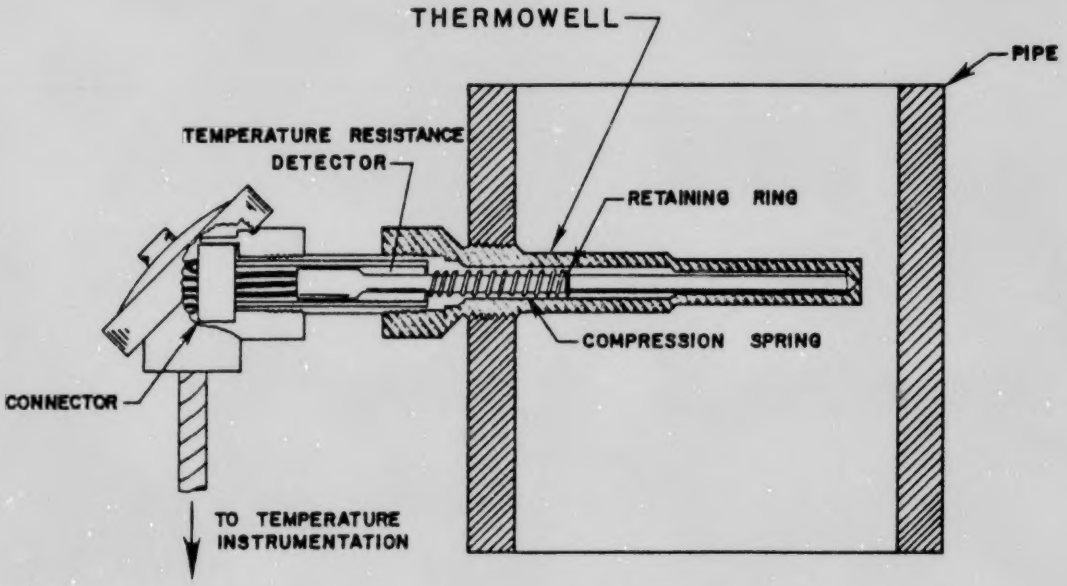


Figure 3-3-3. Resistance temperature detector and thermowell.

The final choice of RTD detailed structure depends on such requirements as desired response time (discussed in Module 3-1, "Temperature Sensing Devices: Glass-Bulb Thermometers"), accuracy, range, compatibility of resistance material with environment being measured, depth of immersion, expected mechanical and thermal stresses, and radiation field.

RESISTANCE THERMOMETER MEASURING INSTRUMENTATION

Measurement of temperature with an RTD reduces simply to measurement of electrical resistance of a known material. Techniques, which are well known, and highly accurate, are used. And values are not difficult to obtain.

The Wheatstone bridge circuit and digital voltmeter studied in basic electricity are the most common instrumentation used in measuring resistance. Basic components of such a measuring system include a resistance element assembly, a signal and compensating lead wires, a bridge circuit and a voltmeter. Incorporation of a recorder with amplifier, servomotor, slide wire and temperature scale completes a typical system for practical plant use (Figure 3-3-4). Two relative low-resistance leads, A and B, connect the thermometer resistor and its lead wires into the Wheatstone bridge circuit. These connecting leads are conventional copper wires, which also have a significant temperature coefficient of the same order of magnitude as that of the thermometer resistor.

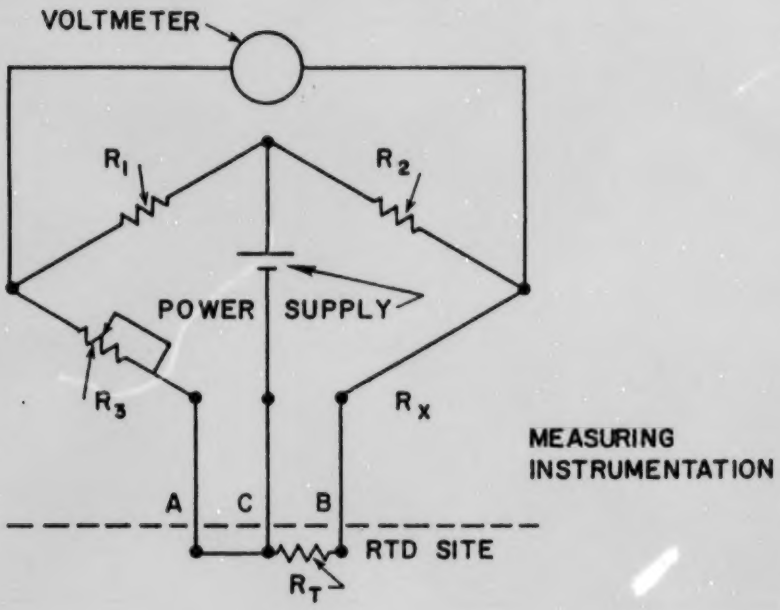


Figure 3-3-4. Basic components of an RTD.

Leads such as A and B also have resistance that may introduce large and uncertain thermometric errors into the measurement of temperatures, especially if differences exist in ambient temperatures along these leads. One method of compensating for this potential error is addition of a third lead wire, C. If lead wires A, B and C are of equial size, length and material, and reside in the same ambient temperatures, then, by using the above variation to the bridge circuit, the effects of temperature on leads A and B will cancel out. This occurs because C is common to both the left and the right loop. The circuit equations for this widely used three-lead measuring circuit may be stated as follows:

$$R_1 + R_3 + A + C = R_T + B + C \qquad \text{Eq. 3-3-2}$$

$$A = B$$

(and, at balance) $R_1 = R_2$

$$\therefore \quad R_3 = R_T. \qquad \text{Eq. 3-3-3}$$

The above three-lead measuring circuit is the most widely used of industrial RTD's, and is called the Siemens arrangement. A still higher degree of accuracy can be acquired by using a four-lead measuring circuit, which averages the sum of two alternate bridge measurements. This set-up, called a Callendar arrangement, is used only where the highest of accuracy is required. Note: The two-lead circuit is the simplest, but also the least accurate.

Variable resistor R_3 (Figure 3-3-4) is used to obtain a null condition on the galvanometer. To mechanize RTD temperature measurements for industrial use, R_3 is usually replaced by a recorder. This recorder consists basically of two fixed resistors and a slide-wire resistor, plus a recorder amplifier, servomotor and temperature scale. This system (Figure 3-3-5) will automatically give a direct reading of temperature.

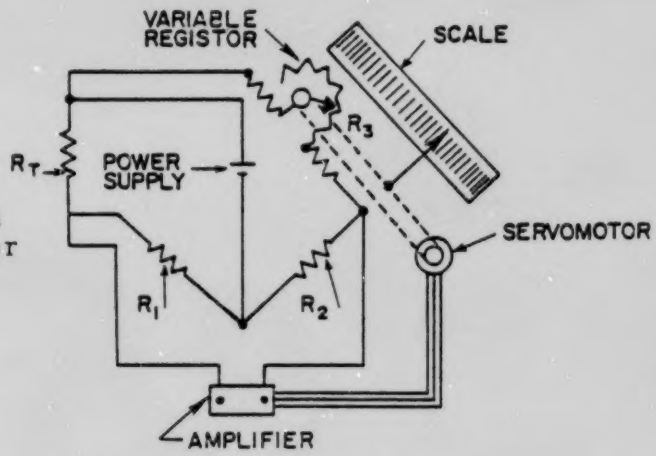


Figure 3-3-5
Resistance thermometer and self-balancing potentiometer recorder.

THERMISTORS

Thermistor type temperature-sensitive semiconductors are similar in principle to RTD's; however, thermistors have much larger but negative resistance temperature coefficients. They are also more nonlinear; as the temperature of a thermistor sensor element increases, its resistance decreases.

Thermistors are relatively small, inexpensive and quite sensitive. When connected in a simple bridge circuit, they can detect a temperature change of as little as 0.0085°C.

The high resistance of thermistors makes their use in locations far removed from the measuring instrumentation attractive because the resistance of long lead wires (400 to 600 feet) are negligible in comparison with that of the thermistor.

Thermistors are essentially semiconductors that behave as thermal resistors; that is, resistors with a high (usually negative) temperature coefficient of resistance. In some cases, for example, the resistance of a thermistor at room temperature may decrease by almost 6% for each °C rise in temperature.

In use, thermistors convert changes in ambient or contact temperatures that correspond directly to changes in voltage or current. They are unusually well rated for precision temperature measurement, temperature control, and temperature compensation because of their very large change in resistance with temperature, which provides a degree of resolution or gain not available with other temperature-measuring systems. Thermistors are widely used for such applications in the range of -100°C to over 300°C.

The thermistor's relatively large resistance change per degree change in temperature provides good accuracy and re-

solution. A typical 2,000-ohm thermistor, with a temperature coefficient of 3.9%/°C at 25°C, will exhibit a resistance change of 78 ohms per °C change in temperature, compared with only 7.2 ohms for a platinum resistance bulb with the same resistance.

Connected to a simple bridge circuit with an indicating galvanometer, a thermistor will readily indicate a temperature change of as little as 0.005°C. It is a simple matter with such a circuit, to obtain a 1°C full-scale output.

This high sensitivity, together with the relatively high thermistor resistance (which may be selected), makes the thermistor ideal for remote measurements or control, since changes in contact or transmission line resistance due to ambient temperature effect are negligible. For example, 400' of #18 AWG copper wire tranmission line, subjected to a 25°C temperature change, will affect the accuracy of measurement approximately 0.05°C.

RTD PERFORMANCE CHARACTERISTICS

Performance characteristics basic to the proper selection and application of an RTD include:

Accuracy.
Repeatability.
Stability.
Sensitivity.
Interchangeability.
Temperature range.

Linearity.
Response time.

Other factors that must be considered are susceptibility to erroneous operations due to self-heating, necessity for the use of long signal leads, and possible radiation damage.

ACCURACY

The accuracy of an RTD is defined as the ability of the sensor to conform to its predetermined resistance-temperature relationship. This accuracy is normally expressed as a percent of the actual temperature reading. For example, a 100-ohm platinum element, reading 100.0 ohms at 0°C, would have an accuracy (or error) of 0.1%. The majority of RTD accuracies fall within the 0.1 to 0.5% range.

There are two principal methods of determining sensing-element accuracy: 1) comparison and 2) fixed-point. The comparison method consists of simultaneous measurement of a test sensor's resistance and that of a close-by certified standard thermometer in the same medium. The standard must follow the International Resistance versus Temperature Curve (IPTS-68) for platinum resistance elements.

Typical RTD accuracies might compare with the standard as follows:

± 0.26°C at 0°C.
± 0.5°C at 100°C
± 1.6°C at 325°C
± 1.9°C at 400°C

Highest calibration accuracy is obtained by the fixed-point method; i.e., the temperature being defined by the change in phase of the same medium. The ice and steam points are measured for the sensor for 0°C and 100°C, and for the tin (231.96°C), zinc (419.98°C) and gold (1065.43°C) melting points. Output accuracies obtained by using the fixed-point method can be within $\pm$ 0.122°C.

To normalize a temperature-measuring circuit to manufacturer's resistance versus temperature scales or curves, a calibration or trimming circuit is provided with the head of the RTD or recorder instrumentation. This ability corrects for the variation of the sensor element's resistance from its nominal value of 100 ohms, and so on, leaving final calibration to the user.

STABILITY

Stability is defined as the ability of a thermometer to maintain its specified resistance-temperature characteristics for long periods of time, within the specified range of temperature. Degree of stability is usually expressed in terms of drift, which is defined as a change in resistance over a period of time. A typical value for drift is $\pm$ 0.05°C; that is, long-term stability effects would cause a change of $\leq$ 0.05°C from its "true" reading over the life of an RTD.

REPRODUCIBILITY

Reproducibility is defined as the conformity of consecutive temperature measurements of a thermometer at a

selected temperature within its specified temperature range of operation.

SENSITIVITY

Sensitivity is defined as the absolute value of the temperature coefficient of resistance affect on the sensor's output signal (i.e., ohms/°C).

LINEARITY

Linearity, in this case, is defined as the departure from linearity of the instrument's resistance relative to temperature. Compare a straight-line (linear) relationship, obtained from Eq. 3-3-1, with an actual relationship obtained from experimental data (Figure 3-3-6). The difference between these two lines is the error, or departure from linearity.

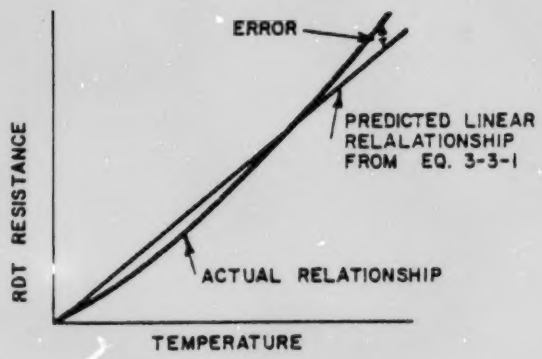


Figure 3-3-6. Illustration of linearity.

This error is significant because actual temperatures are predicted from the linear relationship, not the actual relationship.

RESPONSE TIME

Response time is that time required for the thermometer to react to a step change in temperature and reach the resistance corresponding to 63.2% of the final temperature of the medium being measured. (Refer to Module 3-1, "Temperature Sensing Devices: Glass-Bulb Thermometers.")

SELF-HEATING

An RTD has a passive resistance element and thus requires an external power supply to obtain a signal. In contrast, a thermocouple has an active element, which produces a signal without the application of external power. Because a current must be supplied to the RTD to develop an output signal, heat is generated in the resistance element (i.e., I^2R heating occurs, where I is the current in amps and R is the sensing element's resistance in ohms). This self-heating effect can change temperature measurement by giving an erroneous change in resistance. The effect may be compensated for by using three lead wires (instead of two) in a Wheatstone bridge arrangement (Figure 3-3-4).

LONG SIGNAL LEAD WIRES

If the ambient temperatures around long signal transmission leads are not the same, these temperature differences can indicate an erroneous change in resistance and, in turn, affect accuracy of the temperature measurement. This effect can be minimized by the use of three or four lead-wire measuring circuits, as well as by the use of

identical size, length and material in the leads. Also, by placing all leads in close proximity throughout their length, the problem is lessened.

RADIATION EFFECTS

Neutron and gamma-ray radiation can have harmful effects upon the resistance of a sensing element, and upon the dielectric properties of insulating materials (if radiation is intense enough). Also, such radiation can, under certain conditions, induce electric currents in conductor materials.

PROPER USE AND OPERATIONAL ERRORS

In using an RTD, certain hints may aid in minimizing errors:

1. When lead-wire terminal connections are made, be sure that the identical clamps, terminals and leads are used.
2. Avoid "contact" resistance points, which lead to local hot spots caused by high resistance. (Gold-plated terminals are used for high-accuracy calibration equipment and bridges.)
3. Do not assume interchangeability of units or materials supplied by different manufacturers - not even identical items. (Uniformity of products is not that well established.)
4. Use clean tools when connecting leads.
5. Check operability of any dropped or otherwise maltreated unit.
6. Be sure that accuracy and response time of unit meets requirements of intended application.

7. Be sure that long leads are bundled and laid in a common tray or conduit.
8. Keep leads away from other electrical leads.

ADVANTAGES AND DISADVANTAGES

The advantages and disadvantages of a resistance thermometer may be compared with an accepted counterpart, the thermocouple. Advantages of an RTD include:

High development.

Economy.

Commercial availability.

Greater accuracy.

Idealness for measuring differences in temperature (delta temperature).

Much higher output voltage.

Easier coupling of recorder.

Ease of controlling or trimming of equipment.

Elimination of reference-junction temperature (compensating) devices.

Toleration of more electrical noise (because of higher output voltage).

Greater sensitivity to small temperature changes.

Table 3-3-2 gives a quantitative comparison of sensor characteristics most improtant to RTD selection.

TABLE 3-3-2
COMPARISON OF SENSOR CHARACTERISTICS

	THERMOCOUPLE	RTD	THERMISTOR
Reproducibility	0.5°F to 1.5°F	0.05°F to 0.1°	0.2°F to 2°F
Stability	1° to 2° drift per year	Less than 0.10% drift in five years	0.2°F to 5°F drift in one year
Sensitivity	10 to 50 ohms/°C	0.2 to 10 ohms/°C	100 to 1000 ohms /°C
Interchangeability	± 0.75%	± 0.5%	± 0.5%
Temperature Range	-300°F to 3100°F	-200°F to 1600°F	-150°F to 550°F
Signal Output	0 to 60 millivolts	1 to 6 volts	1 to 3 volts
Power (with 100 ohm load)	1.6×10^{-7} watt	4×10^{-2} watt	8.1×10^{-1} watt
Minimum Size	0.015 inch diam.	9/32 inch diam. x 1/4 inch long	0.014 inch diam.
Unique Features	Greatest economy; highest range	Greatest accuracy over wide spans; highly stable	Greatest sensitivity; lead effects minimized by high impedance
Linearity	Excellent	Excellent	Poor

CALIBRATION AND TESTING

Because of its high accuracy, selection of a resistance thermometer for industrial use is favored. Accuracy achieved depends principally on calibration of resistance thermometer (and associated support components used) over the specified temperature range of intended operation. Manufacturers and professional societies have developed calibration methods for this type of thermometer.

STANDARD PLATINUM RESISTANCE THERMOMETER

The hierarchy of standards was discussed in Module 3-1, "Temperature Sensing Devices: Glass-Bulb Thermometers." There, the establishment and maintenance of temperature standards and scales for industrial and research laboratories was identified as the responsibility of the National Bureau of Standards (NBS). In essence, instruments calibrated by the Bureau become the primary standards used by industry to calibrate their working (i.e., secondary) standards. The platinum resistance thermometer is one of the three principal calibration instruments used in NBS calibrations. This instrument, in turn, is used to calibrate other resistance temperature thermometers, thermocouples and glass-bulb thermometers.

A standard resistance thermometer is constructed of platinum such that the ratio of its resistance at 100°C to that at 0°C is 1.3920 [i.e., its temperature coefficient of resistance is 0.00385 Ω/Ω (°C)] over this range. These resistances are based on the International Practical Temperature Scale (IPTS).

By the use of very special and highly controlled fabrication techniques, high-precision bridges or potentiometers, gold or platinum leads and a constant and known value of resistance, the accuracy of this standard can be ascertained. Platinum resistance thermometers are used as a standard for industrial thermometers throughout the world. The four fixed points of calibration for this standard are the triple point of water and the boiling points of oxygen, steam and sulfur.

USERS CALIBRATION

The following discussion describes the sequence of events that occurs in the manufacture, acquisition, calibration and rechecking of a commercially available RTD. It is assumed, for simplicity, that the RTD discussed is to be used in the range of 0°C - 100°C.

The base resistance (exclusive of lead-wire resistance) of a manufacturer's RTD is measured at the ice point, 0°C. This standard base (reference) resistance is nominally 100 ohms. [Other units of base resistance (200, 400 ohms, etc.) are available.]

To make an accurate and repeatable temperature measurement, the RTD user must adjust or trim the circuit that measures resistance as a function of temperature. This trimming or conditioning is based on an RTD calibration furnished by the manufacturer. The basis for the requirement is the fact that manufacturing an RTD with precisely 100-ohm resistance at 0°C is not always practical or economical. Instead, nominal 100-ohm wires are constructed and calibration curves, by model or series, are furnished to the user for trimming the measurement circuitry.

There are three optional methods for calibration, each with different degrees of accuracy. The user determines a choice by the application requirements of the RTD:

1. The sensor is manufactured to follow a nominal resistance-versus-temperature curve, based on a specific ice-point resistance tolerance of $\pm$ 0.1°C. The user receives a nominal resistance-versus-temperature table, which may be expressed in terms of the ratio R_T/R_0. In general, this method is the least accurate.
2. The sensor is calibrated according to a user-selected calibration schedule, and a resistance-versus-tempera-

ture table is generated. The user then receives the table with the RTD, which affords an intermediate degree of accuracy.

3. The greatest accuracy comes from an ice-bath calibration. The ice and steam points are measured for the sensor, and a resistance-versus-temperature table is generated (Table 3-3-3 is an example). This table also represents the interchangeability a manufacturer would guarantee for a specific series of RTD's.

TABLE 3-3-3
TYPICAL RESISTANCE VERSUS TEMPERATURE TABLE
(NOMINAL 100-OHM ELEMENT)

°C	Equiv. °F	Resistance	± Ohms	± °C
600°C	1112	317.65	0.60	1.83
537.78	1000	297.03	0.56	1.67
500	932	284.30	0.52	1.53
400	752	249.78	0.44	1.25
300	572	214.09	0.36	0.99
200	392	177.23	0.28	0.75
100	212	139.20	0.20	0.52
0	32	100.00	0.10	0.25
-17.7	0	92.91	0.10	0.25
-50	-58	79.95	0.06	0.15
-73.3	-100	70.48	0.05	0.12
-100	-148	59.54	0.05	0.12
-200	-328	17.12	0.09	0.21

On receipt of an RTD, the user may select either a fixed-point ice-bath method of calibration or a water-bath and glass-bulb thermometer comparison calibration method. But a secondary platinum standard, controlled by the calibration laboratory, offers yet another possibility.

The fixed-point ice-bath calibration method of glass-bulb thermometers was covered in Module 3-1, "Temperature Sensing Devices: Glass-Bulb Thermometers." This method is similarly applicable for RTD, except that the test RTD is placed in the bath along with a calibrated precision glass-bulb thermometer.

A comparison calibration method is most commonly used. A large water bath, with an electric heater and motorized stirrer, is set up near the planned installation point of the test RTD. The side of the water-bath container is insulated to minimize heating and cooling. An NBS traceable glass-bulb, totally immersible, stem thermometer is placed in the water along with the RTD. The opposite end of the three long output lead wires (from the RTD) are connected to a portable bridge that has been calibrated in ohms or temperature corresponding to the nominal 100-ohm standard. Beginning at a low, stable, bath temperature, the bridge is balanced and the glass-bulb thermometer read. This step is repeated at incrementally higher stable temperatures that bracket the desired operating region of the RTD. The results should agree with the manufacturer's furnished table, and the data may be used to trim the recorder to match the glass-bulb thermometer temperature.

Next, a decade resistance box, with an accuracy of from 4 to 6 times the desired accuracy of the RTD, is connected to a temperature recorder or meter. The recorder's amplifier is then tuned by the zero- and span- adjustment screws so that the temperature agrees with the calibrated temperature-versus-resistance data from the water-bath.

For a multipoint recorder, where a number of inputs must go through the circuit (Figure 3-3-4), linearizers are provided in the assembly head of each RTD housing for indi-

vidual channel trim. In this way, each channel is trimmed to give a correct temperature reading at the output.

Factors important to the accuracy of calibrations include an adequate number of sample test thermometer results to ensure statistical validity. The approach used by manufacturers of RTD's is to calibrate their platinum RTD by measuring resistance at various fixed points. Instruments used in either of the above methods of calibration require an accuracy four to ten times as great as that of the tested thermometer.

The following items can introduce errors in the calibration of an RTD as well as give erroneous information during operation:

- Poor contact at connector (corrision, looseness or insulation interference).
- Too many and improper splices in RTD leads.
- Maltreatment of unit.
- Fracture of ceramic insulation.
- Lack of proper calibration of support instruments (e.g., decade resistance box).

THERMOWELLS

Thermowells for resistance thermometers are identical to those used for thermocouples and glass-bulb thermometers, except for dimensional changes necessary to accomodate specific RTD's used. Module 3-1, "Temperature Sensing Devices: Glass-Bulb Thermometers," covered thermowells in considerable detail. Figure 3-3-3 details a resistance element assembly in a protecting thermowell. This spring-

loaded design ensure that the elements and well are in constant and firm contact, thus assuring vibration response as a single unit leading to improved response time. This type of dry well is the most common and preferred assembly in power plants.

APPLICATIONS

The two most widely used temperature measuring instruments in power plants are the electrical-resistance thermometer and the thermocouple. Because of the design and heat source of fossil fuel plants (i.e., flames, combustion, flues, tubes and so on), the thermocouple is used more extensively. In nuclear plants (where increased accuracy, fast response, type of heat source, importance of rigorous control of temperature of reactor fuel and coolant and systems designs dictate), RTD's are more dominant.

Depending on the manufacturer, the primary reactor coolant system of a nuclear power plant uses RTD's to measure inlet (cold leg) and outlet (hot leg) coolant temperatures, and to obtain differential temperature rise and average temperature of reactor coolant. Also, they are used to measure the primary inlets (hot legs) and outlets (cold legs) of steam generators, where temperature rises are across the secondary side of the main condenser, and for a host of similar measurements on heat exchangers, reheaters, and the like.

RTD application varies from plant to plant, with the choice between them and thermocouples being dependent on specific needs and engineering preferences.

EXERCISES

1. Measurement reveals a platinum RTD's R_T (resistance at a specific temperature) at 50°C to be 119.75 ohms. By assuming resistance of the RTD to be 100 ohms at 0°C, determine resistance at 100°C.
2. Determine temperature coefficient of resistivity for the above RTD; assume total linearity. [Use $R_T = R_O (1 + \alpha T)$ for determination.]
3. If the above RTD had been a typical thermistor, what direction and magnitude of response could be expected?
4. In calibrating an RTD, what are some of the most common sources of error? How are they minimized?

MATERIALS

1 RTD open-wire element, 100 Ω.
1 RTD standard platinum, 100 Ω (-20°C to 200°C range).
1 thermowell to house a standard 100 Ω RTD.
2 glass-bulb thermometers -20°, -110°C, 0.1°C subdivisions, ± 0.5°C accuracy.
2 insulated 1 to 5 liter beakers.
1 hotplate, with on-off switch.
1 stop watch.
10 pounds of crushed ice.
1 motorized stirrer.
1 portable bridge for 100 Ω platinum RTD, scale in ohms.
1 RTD temperature recorder (meter), 0°C to 150°C.
1 decade resistance box (5 place).

1 digital voltmeter, 3.5 digit (0-50 mv).
3 100-foot copper lead wires.
3 ring stands.

PROCEDURES

TEMPERATURE VERSUS RESISTANCE CALIBRATION CURVE

1. Set up ice bath, water bath and portable bridge as shown in Figure 3-3-7. Cool water bath down to ∿ 20°C with ice.

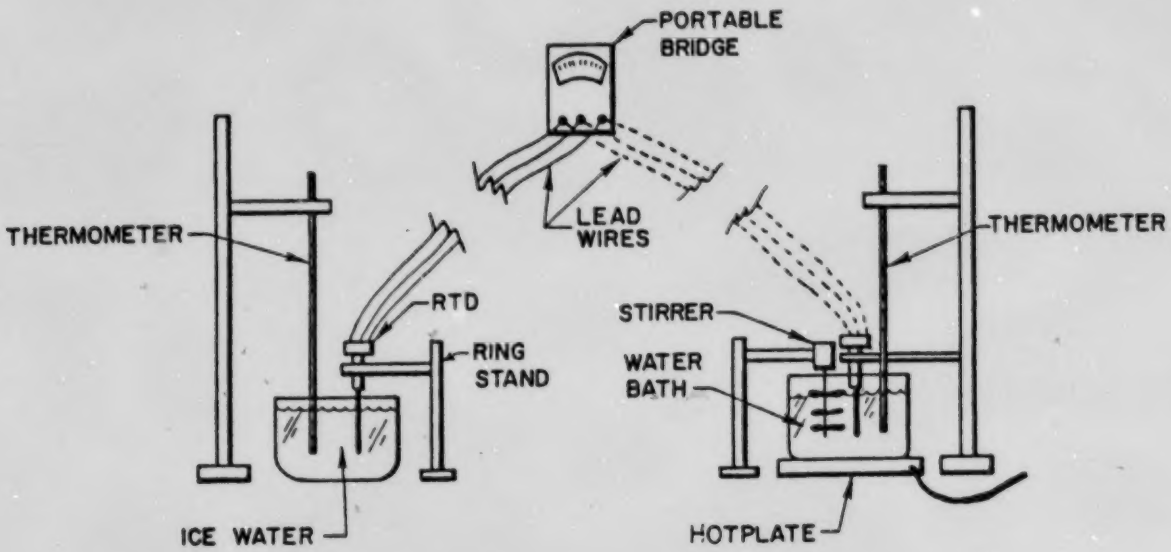


Figure 3-3-7. Component arrangement for temperature versus resistance laboratory procedure.

2. With three-lead RTD in ice bath, and glass-bulb thermometer inserted and supported, read and record resistance and temperature on Data Table 3-3-1.
3. Place RTD in water bath; allow it to come to thermal equilibrium. (Keep stirrer rotating.)
4. Observe and record glass-bulb thermometer and portable bridge readings simultaneously on Data Table.
5. Use hotplate to increase temperature of water bath by approximately 5°C increments; allow bath to come to thermal equilibrium (no more than 1°C drift per 5 minutes). After each change, record glass-bulb temperature and resistance in ohms.
6. Plot ohms versus thermometer temperature on linear graph paper.
7. Is graph linear? Explain possible causes of any deviations.
8. With water bath boiling, loosen terminals on bridge holding lead wires A, B and C (enough for contact only); compare resistance to that obtained when wires were tight during development of resistance-temperature data; record data on Data Table 3-3-1, Part 2; explain any differences.
9. Retighten leads A and B. Remove compensation lead, C. Record data on Data Table 3-3-1. Compare resistance to that obtained in step 5, above. Explain any differences.

TEMPERATURE RECORD CALIBRATION

1. Connect decade resistance box to recorder.
2. At the direction of instructor, zero recorder for 20°C

(in accordance with the vendor's manual).

3. Assume a desired operating temperature range of 20°C ± 10°C; adjust span and zero settings of recorder to 20°C resistance (found on calibration curve developed above for the RTD).
4. Replace decade box leads to recorder with 100-foot leads from RTD. Re-immerse RTD in water bath and cool bath to approximately 20°C.
5. Null bridge and record ohms; read recorder's temperature; explain any differences.

TIME OF RESPONSE TEST

1. Prepare ice bath in same manner as in Module 3-1, "Temperature Sensing Devises: Glass-Bulb Thermometers."
2. Set up ice bath and water bath as shown in Figure 3-3-8.

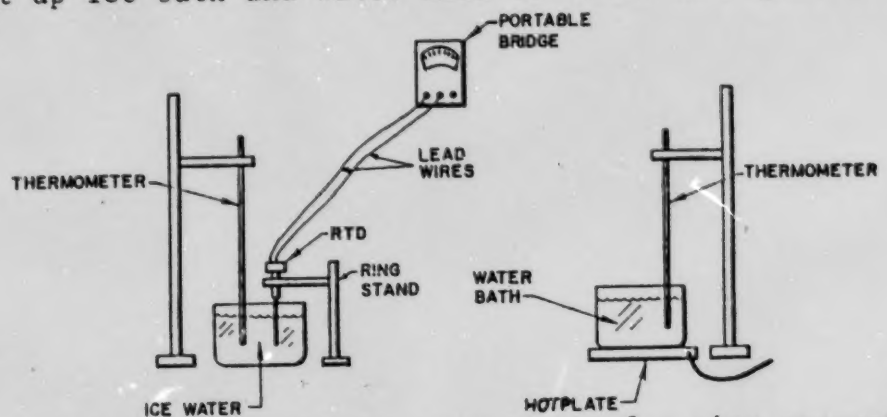


Figure 3-3-8. Component arrangement for time response procedures.

3. Heat water bath to approximately 70°C.
4. Place open-wire RTD in ice bath and allow the ice bath

and water bath to reach thermal equilibrium; connect portable bridge.

5. Set portable bridge at 63% of temperature difference (in ohms) between ice bath and water bath (45°C).
6. Quickly remove RTD from ice bath and plunge it into water bath; simultaneously start stop watch.
7. Terminate stop watch when bridge indicates nulled condition of 63% temperature rise has been reached. Record time on Data Table 3-3-2, Part 1.
8. Repeat steps 4 through 7 above, using RTD-thermowell assembly.
9. Repeat steps 4 through 7 above, using a digital voltmeter. (Instructor will set up voltmeter with portable bridge to demonstrate millivolt change per °C experienced with RTD's and, in turn drive recorders.)

DATA TABLE

DATA TABLE 3-3-1

TEMPERATURE VERSUS RESISTANCE CALIBRATION CURVE

Part 1.

Type of Resistance Material _____

Type of RTD _____

	Temperature °C (Glass-Bulb)	Resistance (Ohms)
1.	0°C	
2.		
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		
11.		
12.		
13.		
14.		
15.		
16.		
17.		
18.		
19.		
20.		

DATA TABLE 3-3-1 (Continued)

Part 2: Loose Lead Wires (3)

Ohms from Calibration Curve: _____ohms.

Ohms with Loose Wire: _____ohms.

Difference: _____ohms.

Explain:

Part 3: Uncompensated RTD

Three Wires (Boiling Water): _____ohms.

Two Wires (Boiling Water): _____ohms.

Difference: _____ohms.

Explain:

Part 4: Calibration of Recorder

Portable Bridge Output: _____ohms.

Recorder Temperature: _____ohms.

Calibration Curve: _____ohms.

Calibration Curve: _____ohms.

Difference: _____ohms.

Difference: _____ohms.

Explain:

DATA TABLE 3-3-2
TIME OF RESPONSE

Type of Resistance Material: _____

Type of RTD: _____

Part 1. Bare RTD

Ice-Bath Temperature °C	Water-Bath Temperature °C	63% Temperature °C	Time Seconds

Speed of Response: _____

Part 2. Thermowell RTD Assembly

Ice-Bath Temperature °C	Water-Bath Temperature °C	63% Temperature °C	Time Seconds

Speed of Response: _____

Determine difference between the times in Parts 1 and 2.

Explain:

Considine, D. M. ed. Process Instrumentation and Controls Handbook. 2nd ed. New York: McGraw-Hill, 1974.

Harrer, J. M. and Beckerly, J.G. Nuclear Power Reactor Instrumentation Systems Handbook, Vol. 1. Springfield, VA: U.S. Atomic Energy Commission, Office of Information, Technical Information Center, 1974.

Loeffer, R. F. "Thermocouples, Resistance Temperature Detectors, Thermistors - Which." Instruments and Control Systems (May 1967):89.

Moore, R. L., ed. Basic Instrumentation Lecture Notes and Study Guide - Measurement Fundamentals. 2nd ed. Pittsburgh, PA: Instrument Society of America, 1976.

National Physical Laboratory. International Practical Temperature Scale of 1968. English version of official French text from the 13th General Conference of Weights and Measures. London: Her Majesty's Stationery Office, 1969.

Omega Engineering, Inc. Temperature Measurement Handbook. Stamford, CN: Omega Engineering, Inc., 1976.

Sostman, H.E. "Resistance Thermometers." Instruments and Control Systems (October 1966):117.

TEST

Read each question carefully. Be sure your responses give the specific information each question requires. Your answers should be brief. Use the backs of the test if you need more space.

1. What does a resistance temperature detector (RTD) measure?

2. List three disadvantages of a resistance temperature detector (RTD) as compared to a thermocouple.

   a.

   b.

   c.

3. What is the principle of operation of the RTD?

4. What is the temperature coefficient of resistance for a material?

5. List four basic requirements for a good resistance thermometer's sensor element.

   a.

   b.

   c.

   d.

6. Write an equation that expresses the relationship between resistance and temperature for pure metals. Define terms in the equation.

7. What <u>two</u> metals are used most often in the fabrication of sensor elements?

_____

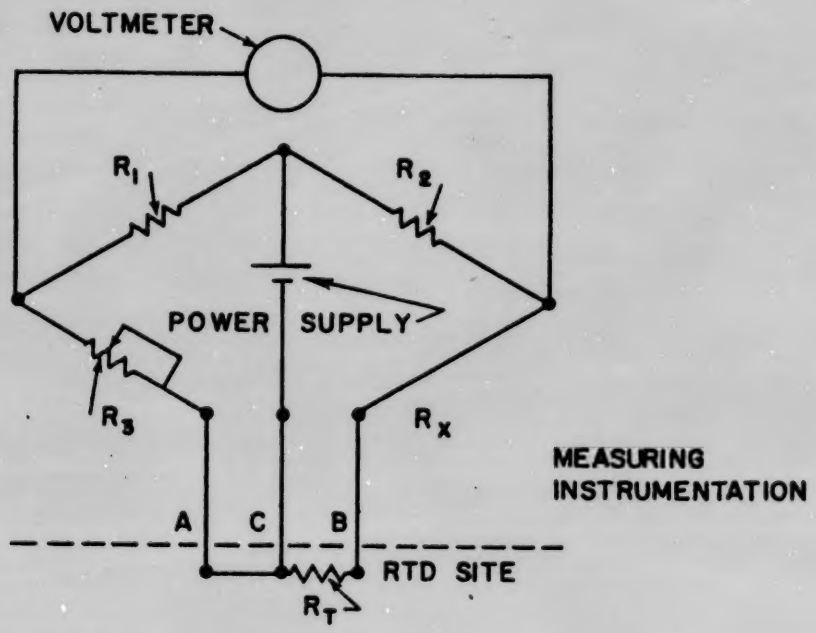
8. What is one condition in the plant environment that would make it desirable to insert the RTD into the thermowell tubes in order to use it? What is one advantage of the thermowell tube?

_____

_____

_____

9. Study the drawing of the basic components of an RTD and answer the questions about the drawing.



a. What purpose do A and B serve?

_____

b. What is the purpose of C?

_____

c. What is the Siemens arrangement?

_____

d. What is R_3? What is R_3's purpose?

_____

e. In industrial use, what device generally replaces R_3? Why?

_____

10. How is a thermistor different from an RTD?

11. Why are thermistors well-suited for precision temperature measurement temperature control, and temperature compensation?

12. Why is a thermistor ideal for remote measurements or control?

13. What does the term "accuracy" of an RTD mean?

14. Briefly describe one method of determining a sensor's accuracy.

15. Over the lifetime of an RTD, what would be a typical value for drift?

16. Define sensitivity as it pertains to an RTD.

20. What is one possible effect of neutron and gamma radiation on a sensor?

21. List three guidelines for reducing or minimizing error when using an RTD.

a.

b.

c.

22. Compare thermocouples, RTD's, and thermistors as to the following characteristics: stability (assuming minimum drift), sensitivity, temperature range, and linearity.

Stability:

Sensitivity:

Temperature Range:

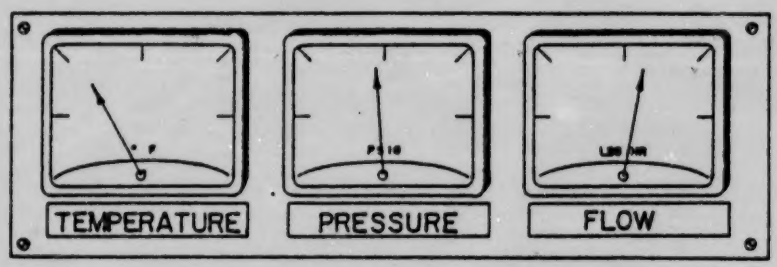
Linearity:

23. What is the primary standard used in the National Bureau of Standard's calibration of industrial thermometers?

24. Assuming you have a suitable resistance versus temperature curve, describe how to calibrate an RTD system using a decade resistance box.

NUCLEAR TECHNOLOGY

MODULE 3-4 TEMPERATURE-SENSING DEVICES:
PYROMETERS



PRINCIPLES OF
PROCESS INSTRUMENTATION

COURSE 3

COURSE MODULES

COURSE 3 PRINCIPLES OF PROCESS INSTRUMENTATION

MODULE 3-1	Temperature-Sensing Devices: Glass-Bulb Thermometers
MODULE 3-2	Temperature-Sensing Devices: Thermo-couples
MODULE 3-3	Temperature-Sensing Devices: Resistance Thermometers
MODULE 3-4	Temperature-Sensing Devices: Pyrometers
MODULE 3-5	Basic Principles of Flow Measurement
MODULE 3-6	Pressure-Sensing Devices
MODULE 3-7	Flow-Sensing Devices: Differential-Pressure Flowmeters
MODULE 3-8	Flow-Sensing Devices: Linear Flowmeters

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INTRODUCTION

The concept of pyrometers stems basically from determinations of the temperature of a body by measuring its broadband optical radiation (associated with heat emitted from body).

Such terms as "red hot" and "white hot" infer degrees of emitted thermal radiation. By an appropriate combination of optical components, such as lenses, filters and mirrors, and by the use of thermocouples, heated wires, and the like, the temperature of a body may be determined by measuring quantity and characteristics of the energy emitted from that body.

The term pyrometer has been applied to two categories of instruments: "contact" and "noncontact." The former normally refers to thermocouples and resistance temperature type devices studied previously. The latter is useful as a remote reader.

This module discusses noncontact pyrometers in terms of their principles of operation, design, performance characteristics, calibration and applications. Sources of errors, as well as advantages and disadvantages, are also discussed. Sufficient theory is presented to enable the student to understand how a pyrometer operates, why it has limitations, and to recognize operational difficulties associated with it.

Applications of pyrometers to steam electric power plants as "process instruments" is limited, especially for nuclear plants. Pyrometers are frequently used, however, for hot-spot surveys or thermal mapping in fossil-fueled boilers and, on special occasions, in nuclear plants. Also, there are uses for pyrometers outside the

power plant; for example, in switchyards and at gas-turbine peaking stations.

Finally, a procedure is provided to demonstrate temperature measurement with a pyrometer, and how results may be checked with a high-precision platinum thermocouple.

MODULE PREREQUISITES

Module 3-2, "Temperature Sensing Devices: Thermocouples," should be completed as a prerequisite to study of this module.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define or describe the following terms and concepts including usual units where applicable:
   - Radiation pyrometer.
   - Wavelength.
   - Optical pryometer.
   - Frequency.
   - Spectrum.
   - Thermal radiation.

Stefan-Boltzmann law.
Blackbody.
Nonblackbody.
λ_{max}.
Wien's displacement law.
Gray body.
Receiver element.
Red glass filter.
Emissivity (emittance).

2. Explain the basic principles used in pyrometer operation, including σT^4 principle, emissivity, transmission and detection of thermal radiation.
3. Describe basic components of pyrometers, with specific reference to the interplay of radiation and optics.
4. Sketch basic functional components of radiation and optical pyrometers.
5. Identify and describe factors that influence suitability (selection) of a pyrometer.
6. Discuss factors involved in emission of thermal radiation from hot sources.
7. Discuss key factors important to the application and maintenance of a pyrometer.
8. Make emissivity corrections for an optical pyrometer; use suitable table and give pyrometer readings.
9. Describe calibration methodology and use of references and standards (NBS and platinum thermocouple).
10. Identify four useful pyrometer ranges.
11. List at least three industrial uses of pyrometers (include power-plant application).
12. Use pyrometer to perform temperature measurements at a kiln or similar furnace that approaches blackbody

status; compare readings with temperatures obtained with a thermocouple.

NONCONTACT TEMPERATURE MEASUREMENT

Past modules have discussed measurements of certain physical changes in materials as functions of temperature (e.g., resistance and thermal expansion). These changes, in turn, were correlated to actual temperatures or temperature changes of the materials. At the same time, these methods of measurements required physical contact with the medium being measured. There are, however, numerous situations that require making temperature measurements where physical contact with the medium is neither practical nor possible; for example, a pour of molten steel, inside of a boiler tube, or a very high voltage transmission line insulator or breaker in a switchyard, or in a moving object such as a rocket. All of these applications require visual (line of sight), noncontact temperature-measuring techniques.

In addition to conventional pyrometers, sometimes referred to as "radiation thermometers," there are other indirect, noncontact devices for measuring temperatures; e.g., photosensitive films, solid-state devices and semiconductors. These latter types of pyrometers find very limited use at nuclear power plants.

The two major, and most frequently used, commercial groups of pyrometers are classified according to the method they employ in measuring temperature. The first group, radiation pyrometers, measures radiation from an object over a wide band of wavelengths; i.e., it measures total rate of energy emitted per unit area of source. The second group, optical pyrometers, measures radiation from an

object over a narrow band of wavelengths; i.e., it compares brightness of the object with a source of standard brightness incorporated into the pyrometer.

Pyrometer accuracy and application depends on many factors, including heat emission qualities of source materials, physical limits of measuring equipment, type of source, calibration, and proper instrument use and maintenance.

PRINCIPLES OF OPERATION

Before discussing the phenomenon of radiation and the principles of its measurement, a short review of some basics is in order. Radiant energy is a form of energy that travels as electromagnetic waves. These waves are characterized by their frequency or wavelength:

$$c = \lambda f \qquad \text{Equation 3-4-1 (Equation = Eq.)}$$

where

c = speed of light.
λ = wavelength of emission.
f = frequency.

The term "band," or spectral width, refers to the range of wavelengths or frequencies covered.

As a result of the atomic and molecular motion associated with a given temperature, all substances emit rad-

iant energy. The quantity (intensity) and spectral characteristics (wavelength, spectrum) emitted by a body depends on its temperature as well as its composition, geometry, surface characteristics and, if not opaque, its physical dimensions.

The amount of energy emitted is relatively small at low temperatures and great at high temperatures. At low temperatures, the radiation emitted is chiefly in the infrared range, not visible to the human eye; however, all radiations are measurable.

Thermal radiation lies in the wavelength region from about 0.1 to 100 μm (1.0 μm = 10^{-6} m, 1 μm = 1 micrometer).

The total quantity of radiation emitted by a body per unit time and area can be stated in units of Btu/hr/2 or ergs/cm^2 sec. This rate of emitted radiant energy is proportional to the temperature of the body to its fourth power, as given by the Stefan-Boltzmann law:

$$W = q/S = \sigma\varepsilon T^4 \qquad \text{Eq. 3-4-2}$$

where

- q = radiant energy emitted per unit time, Btu/hr (calories/sec) or (ergs/sec).
- S = surface area, ft^2 (cm^2).
- σ = Stefan-Boltzmann proportionality constant, Btu/ft^2/hr/T^4 (ergs/cm^2/sec/T^4).
- ε = emissivity of surface (usually between 0.8 and 0.95 for boiler material).
- T = absolute temperature, in degrees Kelvin (°K). Note: °C + 273 = °K.

This emitted-radiant-energy versus temperature relationship is applicable to a blackbody, which can be defined as a body that absorbs all radiation incident upon it. If such a body is in thermal equilibrium with its surroundings (e.g., an enclosed ceramic brick-lined furnace), it emits radiation at a rate equaling that incident upon it (and thus absorbed by it). If the body is not in thermal equilibrium, or is a nonblackbody, an appropriate "correction factor emissivity," ε, can be applied to describe the actual situation. This latter condition is more typical of power-plant conditions, as noted in Equation 3-4-2.

At low temperatures, radiation is chiefly in the infrared range. As a temperature rises, an increasing proportion of the radiation is in the shorter wavelengths, becoming visible (as a dull red glow) at about 1000°F (810 °K) and passing into a white glow at 2200°F (1477°K). For steel, the color scale in Table 3-4-1 is generally applicable.

TABLE 3-4-1
APPARENT COLOR OF STEELS AT VARIOUS TEMPERATURES

Color	Temperature
Dark Red	1000°F (810°K)
Cherry Red	1250°F (950°K)
Orange	1650°F (117°K)
Yellow	1850°F (1280°K)
White	2200°F (1480°K)

Radiant energy emission (emission power) of blackbodies varies with wavelengths. This relationship of temperature, wavelength and emissive power (Figure 3-4-1) identifies para-

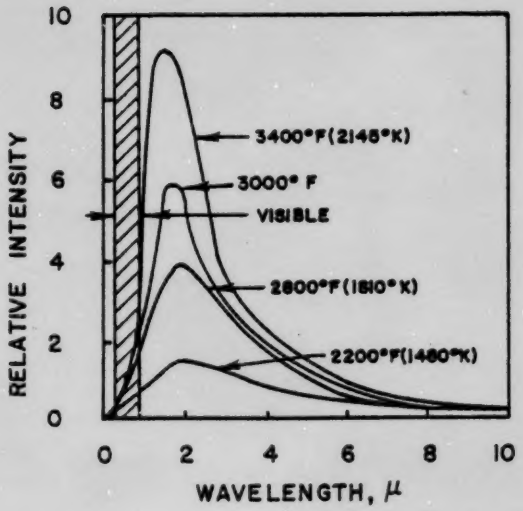

Figure 3-4-1.
Spectral distribution of radiant energy.

meters available and upon which pyrometers are designed. The maximum wavelength of each curve, λ_{max}, depends upon temperature, according to Wien's displacement law, which states:

$$\lambda_{max} T = \text{constant} = 0.2898 \text{ cm } ^\circ K \qquad \text{Eq. 3-4-3}$$

where λ_{max} is in centimeters.

Actual shape of the spectral-distribution versus temperature curve is given by a somewhat complicated mathematical expression known as Planck's law.

In daily practical measurements of temperatures by pyrometry, real heat sources are seldom true blackbodies. The radiation laws are, therefore, modified by introduction of a correction factor to account for the difference between a black and nonblack radiating body, sometimes

called gray body (Figure 3-4-2).

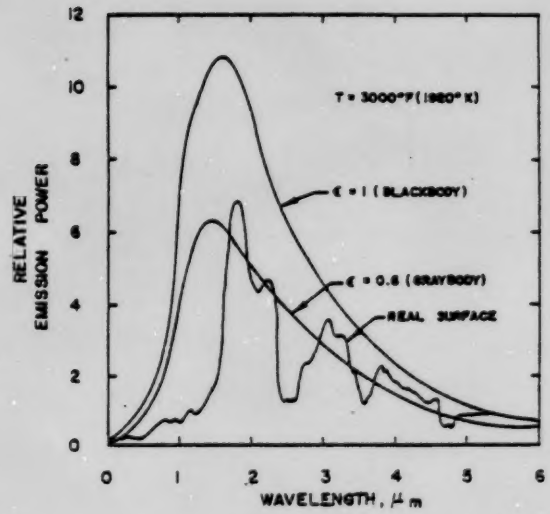

Figure 3-4-2. Comparison of emissive powers of a blackbody, an ideal gray body and an actual surface.

By definition, the emissivity of a blackbody is unity. All other bodies have lower emissivity:

$$\varepsilon = \frac{E}{E_b} \qquad \text{Eq. 3-4-4}$$

where

ε = emissivity.

E = emissive power of an actual surface.

E_b = emissive power of blackbody at same temperature.

Table 3-4-2 lists typical emittances of common materials.

TABLE 3-4-2
EMITTANCES OF COMMON MATERIALS

	Material	State	Typical Emittance
METALS			
	Carbon	Graphite	0.80
	Steel	Solid	0.35
	Uranium	Solid	0.54
OXIDES			
	Alumel	Solid	0.87
	Uranium	Solid	0.30
	Stainless Steel	Oxidized	0.85

TRANSMISSION AND RECEIVER PRINCIPLES

Radiative energy basically consists of an infinite number of streams of photons traveling in straight lines at the speed of light. Photons can be reflected by mirrors and focused by lenses through refraction. Starting a wood fire by using the sun and a magnifying glass is a commonly practiced application of focusing light (electromagnetic) waves.

The relationship of thermal radiation to temperature determination is accomplished by collecting the radiation with optical systems and thermal-detection systems. An optical system collects radiation from a target (thermal source) and focuses it onto a thermally sensitive receiver

element or detector. The detector system may be the human eye, in the case of an optical pyrometer, or a thermocouple or an RTD that converts the total or a portion of the incident thermal energy into some electric signal. The latter systems are called radiation pyrometers.

BASIC PYROMETER DESIGN AND CONSTRUCTION

A basic radiation pyrometer (Figure 3-4-3) is one that

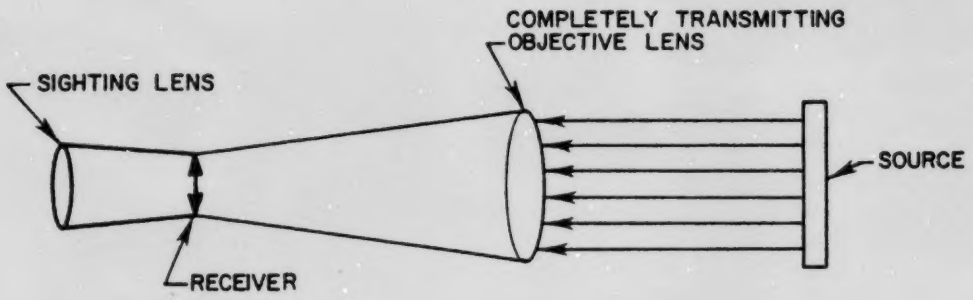

Figure 3-4-3. Radiation pyrometer.

collects all wavelengths of radiation emitted by a thermal-emitting object and focuses and concentrates this energy onto a receiver element. Equation 3-4-1 indicated that the rate at which energy is emitted by a blackbody is a function of the difference of the temperature of the source (or target) and a receiver, to the fourth power.

The temperature change of a receiver element depends on the radiation source's temperature and the area observed, and on the thermal equilibrium formed by the receiver ele-

ment's surroundings. (Note: The Brightness Theorem states that no object is capable of being directly heated to a temperature higher than that of the radiating energy source.)

A most effective method for collecting and measuring broad-band radiating sources uses a thin, black metal strip exposed to the radiation. A thermocouple or thermopile (a clustered collection of thermocouples) may be used for determining temperature of the blacked, radiation-sensitive receiver element.

If the receiver element is a blackened foil material, such as platinum, it can be used as an RTD. This type of pyrometer is called a "bolometer." Other receiving elements used include thermistors and photosensitive devices, such as phototubes, photodiodes or photomultipliers.

Because neither the source nor the receiver element is usually a true blackbody (and for other reasons) industrial radiation pyrometers do not follow the fourth-power law precisely, and do require corrections which are usually furnished by manufacturers of the instruments.

A radiation pyrometer maybe "sighted" on a source or target by observing the image of the source on a mirror or prism when viewed through its sighting lens, (Figures 3-4-3 and 3-4-4).

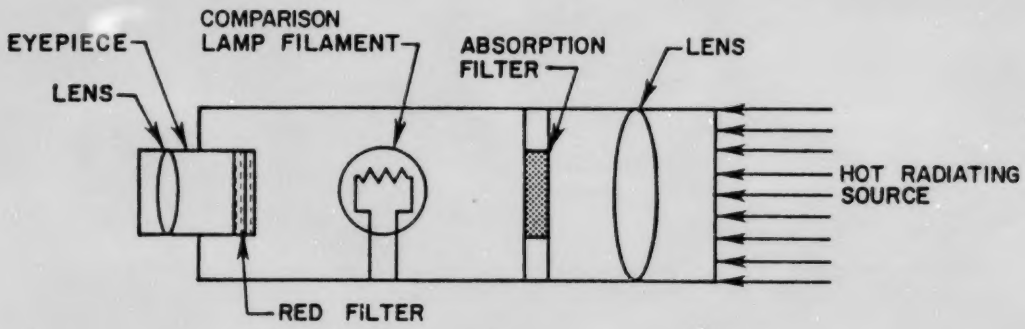

Figure 3-4-4. Optical pyrometer.

Low-temperature (less than 400°F) radiation pyrometers are more apt to be used in a nuclear plant. Such use might occur where a nuclear radiation field prohibits human entry into an area. For low-temperature use, a pyrometer's housing (background environment) temperature must be controlled within $< \pm$ 1°C of a preselected temperature. This control is necessary to offset major internal errors caused by fluctuations in temperatures within the instrument itself.

Other special design features, such as calcium fluoride lenses for transmitting low-temperature wavelengths in the infrared, and auxiliary RTD's for housing temperature monitors and controls, are added design and construction features.

In an optical pyrometer - one that collects only a narrow band of wavelengths - radiation from a source is viewed through the lens and filter arrangement. An absorption filter at the front of the device reduces the intensity of incoming radiation so that the comparison lamp may operate at a lower power level. With the lamp filament in the optical path of incoming radiations, adjustments to the lamp current are made to match the color of incoming radiation. A red glass filter is installed in the radiation path to ensure that color comparisons are made without variations of radiation properties from other wavelengths.

The optical pyrometer measures intensity of radiant energy from a source in a narrow wavelength interval of the visible spectrum. The temperature of the target is then determined from its radiant intensity by using suitable circuits internal to the instrument.

When a balanced condition is achieved between the lamp filament's intensity and that of the incoming radiation, the filament seems to disappear (Figure 3-4-5). Temperature de-

termination are made in terms of lamp-heating current.

Figure 3-4-5. Eyepiece view of lamp filament (optical pyrometer).

The brightness comparison made by the observer depends upon the sensitivity of the human eye to differentiate between two adjacent surfaces of the same color. A glass, color filter, which allows only red radiation to pass, is provided to enhance this matching (nulling).

BASIC CIRCUITRY

Circuitry commonly used in radiation pyrometers, for the measurement of emf or resistance of thermocouples and RTD's respectively, was discussed in Module 3-2, "Temperature Sensing Devices: Thermocouples," and Module 3-3, "Temperature-Sensing Devices: Resistance Thermometers." Integration of these measuring circuits into optical systems allows them to receive and focus thermal-source radiation.

The electrical circuitry of an optical pyrometer is

basically of the resistance heating element type (Figure 3-4-6). The instrument illustrated employs a manual on-off

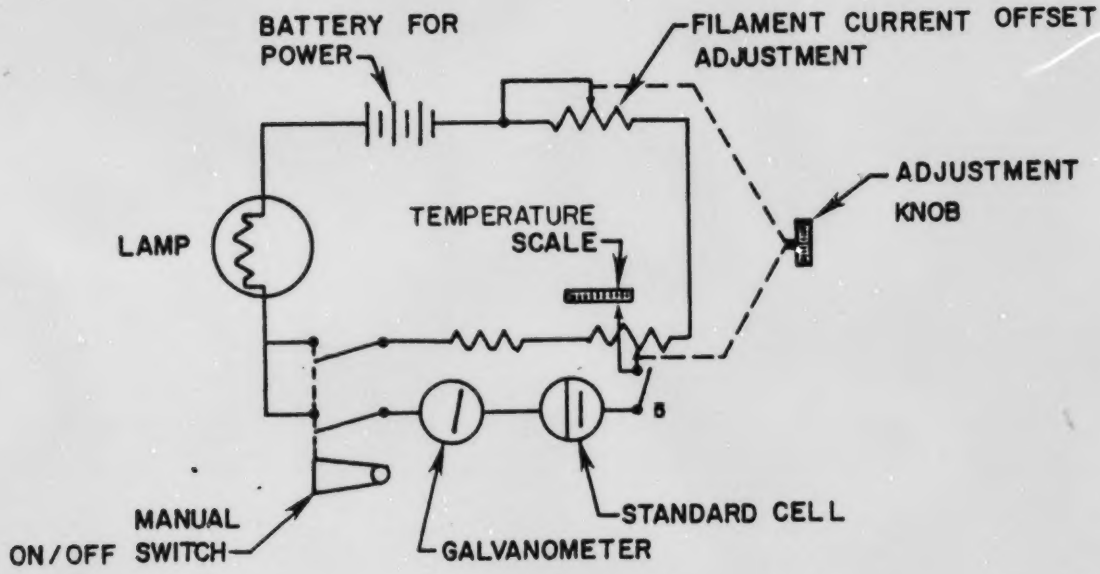

Figure 3-4-6. Circuit diagram of a portable optical pyrometer.

switch on the pyrometer's housing to activate its circuit. When the switch is on, the lamp (filament) circuit is closed. By turning a knob, filament current is adjusted (until the filament disappears). The current adjustment knob moves with the temperature scale, which rotates against a fixed index. A standard cell, with a known and fixed emf, is used to check calibration of the pyrometer.

A radiation pyrometer (Figure 3-4-7) uses a thermocouple

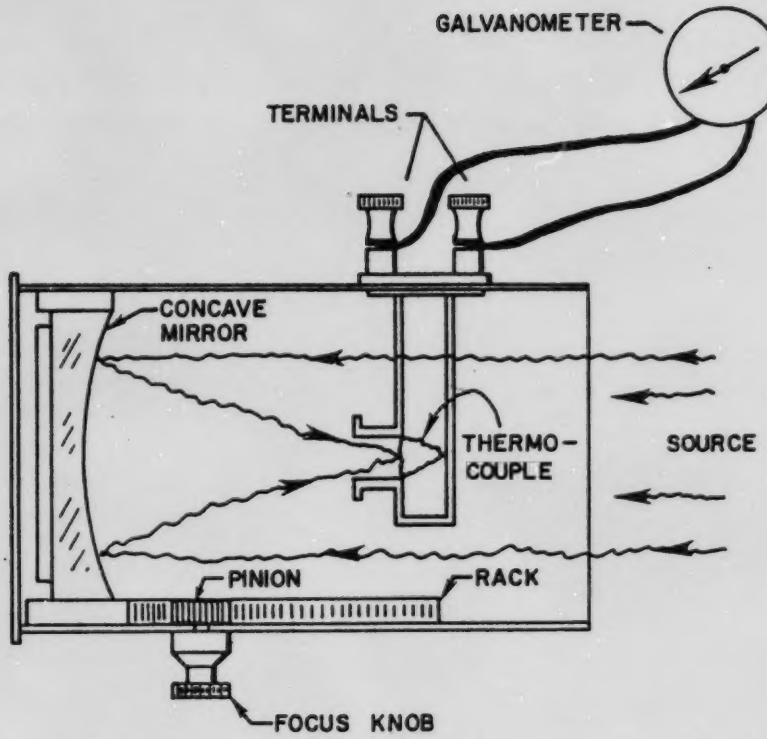

Figure 3-4-7. Circuit diagram of a basic radiation pyrometer.

as its receiver element and a galvanometer for reading out emf relating to temperature.

TYPES OF PYROMETERS

As noted in previous discussions, radiation pyrometry is a method of determining the temperature of an object by measuring thermal energy radiated from it. Four basic types of pyrometers are in commercial and laboratory use.

Total radiation (broadband) pyrometers.
Brightness (optical) pyrometers.
Bandpass pyrometers.
Ratio pyrometers.

The broadband pyrometer is the simplest and least expensive. Generally, it is responsive to radiation from wavelengths from 0.3 μm to 2.5 μm or from 0.3 μm to 20 μm. This upper limit is determined by the transmission capability of an instrument's lens and window material. These instruments are termed total radiation pyrometers because, in the majority of applications, most of the radiation emitted from a viewed source covers wavelengths for which the pyrometer is sensitive.

The brightness (optical) pyrometer, in contrast to the above, measures radiation in a narrow band of wavelengths - specifically in the visible range. These instruments null against the brightness of an internal reference standard. Radiation comparison (in most portable, optical pyrometers) normally is done manually by the operator. But automatic, continuous-reading pyrometers are available.

A bandpass pyrometer's spectral response is selected for a specific application, such as measuring the temperature of a particular material or object, such as a gas-turbine blade or plastic. For low-temperature targets, a pyrometer can be designed to observe targets at great distances. A ratio pyrometer measures radiant energy in two bands of the spectrum.

PERFORMANCE CHARACTERISTICS

Four performance characteristics are especially significant.

SENSITIVITY

In the design of a low-temperature radiation pyrometer, as well as an optical pyrometer, sensitivity is enhanced by the use of special lenses and filters. Sensitivity may be influenced more by the radiation source than by the measuring instrument itself, since slag (on an ingot), smoke, dust or other interferences can obstruct or filter out radiant energy.

The responsiveness of an instrument is hindered principally by the presence of noise in the circuitry; however, seldom is it necessary to consider such noise in pyrometers used in power plants.

TIME RESPONSE

In a radiation pyrometer, one prominent limitation is the relatively slow response of the receiver element to changes in incident energy. This response depends on detector mass, or the receiver element, and heat energy loss to surrounding instrument housing (by radiation and by conduction). Incorporation of specific design features limit commercial instrument time response to about two seconds. Special instruments can provide responses of a fraction of a second.

Optical pyrometer response is almost totally limited by the time required to manually adjust the matching filament. In automatic systems, response time is approximately the same as that provided by radiation pyrometers.

SPECTRAL RESPONSE

Because receiver elements of most conventional radiation pyrometers (bolometers and thermopiles) are usually coated with some wide spectral, highly absorbant material, they are independent of the wavelength of incoming radiation. For instruments that use other types of receivers, spectral response may be more sensitive to wavelength. The optical pyrometer is designed as a narrow, spectral-band instrument.

RANGE OF APPLICATION (TEMPERATURE)

Radiation pyrometers for use in power plant and chemical industry applications normally have a range of 50° to 370°C. These pyrometers may be used down to 0°C in some very special applications, but the normal power plant application is for temperatures above 200°C. An arbitrary range of classification of pyrometers is given in Table 3-4-3.

TABLE 3-4-3
RANGE CLASSIFICATION OF PYROMETERS

Classification	Range °C
Extra High High Range	4200 and higher
Extra High Range	2800 - 4400
High Range	1700 - 2200
Medium Range	500 - 1800
Low Range	70 - 600

When specifying an instrument for a particular application, the specifications should be written so that the temperatures to be measured fall within 60 to 100 percent of the instrument's range. The range of temperature measurements (for optical pyrometers) normally lies between 540°C and 2800°C. With specially selected absorption screens, units can be extended to 6000°C.

Both of the above types of pyrometers are normally constructed with three or four ranges.

PROPER USE AND OPERATIONAL ERRORS

The user of a pyrometer must consider several important features:

Field of view and relationship between required target size and distance to target.

Desired spectral response.

Suitability of window material for intended environment.

Temperature lens (or range) accuracy and response time required.

Sighting a pyrometer becomes more and more important as target size diminishes. Generally, the smaller the target, the more sophisticated the sighting requirement. Sighting means must be as effective as focusing means.

Many industrial radiation pyrometers have field-focus units. These units are simple, reliable and generally not overly susceptible to maladjustments.

Mismatch of a pyrometer to its intended use, failure

to calibrate it, lack of system warmup and target-to-lens medium cause most operational errors.

Measured temperature of the object sighted upon is its apparent blackbody temperature. But, if it is not a true blackbody (i.e., if its emissivity is less than 1.0) or if smoke or fumes are in the line of sight, or if foreign deposits are in the optical system, apparent blackbody temperature will deviate from actual blackbody temperature. Also, the obtainable precision depends upon experience of user and levels of maintenance of equipment.

If emissive properties of a surface are known accurately, pyrometer measurements may be used to calculate true temperature.

EXAMPLE

Given: Emitted energy from a piece of metal is measured by a pyrometer and found to be 1065°C, assuming an emissivity of 0.82. By using a thermocouple the true temperature was found to be 1095°C. (Use Equation 3-4-2).

Solution:

$$W = \sigma \varepsilon T^4$$

$$\varnothing \varepsilon_1 T_1^4 = \varnothing \varepsilon_2 T_2^4$$

$$\varepsilon_1 = 0.82 \qquad \varepsilon_2 = ?$$

$$T_1 = 1065 \qquad T_2 = 1095$$

$$\therefore\ 0.82(1065)^4 = \varepsilon_2(1095)^4$$

$$\frac{\varepsilon_2}{0.82} = \frac{(1065)^4}{(1095)^4}$$

$$\frac{\varepsilon_2^{\frac{1}{2}}}{0.906} = \frac{(32.634)^2}{(33.091)^2}$$

$$\frac{\varepsilon_2^{\frac{1}{4}}}{0.952} = \frac{5.713}{5.752} = 0.993$$

$$\varepsilon_2^{\frac{1}{4}} = 0.993 \times 0.952 = 0.945$$

$$\varepsilon_2^{\frac{1}{2}} = 0.894 \qquad \varepsilon_2 = 0.798$$

CALIBRATION AND ACCURACY

All pyrometer calibrations are classified as either primary, secondary or process. Field calibration is basically a comparison method that uses certified or secondary pyrometers. This approach is taken because of the complexity and expense of maintaining primary standard facilities (as are kept by the National Bureau of Standards). A primary standard is usually of value only to instrument manufacturers and the National Bureau of Standards.

Radiation pyrometer calibration is most often accomplished by comparison with a secondary-standard radiation pyrometer, which is based on a previous calibration. This approach eliminates any need for a blackbody radiation source. Both the secondary-standard and the test pyrometer are exposed to the same fraction of blackbody radiation;

and the test pyrometer circuitry and output are adjusted to agree with the secondary-standard pyrometer's indicated values.

An alternative, and sometimes more accurate, calibration is the "process" method. The test pyrometer is sighted upon a target whose temperature is normally and repeatedly measured. The temperature of the target, in turn, is determined by a thermocouple located in the field of view of the pyrometer, and the pyrometer is adjusted accordingly.

For optical pyrometers, a principle method of calibration is establishment of a calibration curve of filament-current versus temperature, obtained by matching the filament brightness against that of a known blackbody source temperature. Such sources are generally available from the National Bureau of Standards.

A secondary method of optical instrument calibration uses blackbody sources with absorbing screens or a standard lamp source. The latter is used almost exclusively. The scale of the test pyrometer is adjusted to the certified instrument.

In most cases, pyrometer calibration is a matter of transferring a secondary-standard calibration to a field instrument.

The accuracy of radiation (and optical) pyrometers ranges from ±4°C, in the lower range, to ± 25°C in the extra high range. Emissivity corrections for optical pyrometers, as a function of instrument readings, may be found in several references (e.g., Tuve and Domholdt's Engineering Experimentation).

APPLICATIONS IN GENERAL

Radiation and optical pyrometers are capable of measuring temperatures from the low ranges (associated with thermal pollution; e.g., condenser discharge from power plants) up to the extremely high ranges associated with plasma research. The chemical industry monitors and controls inaccessible equipment with pyrometers; the electronic industry locates defective components (e.g., transistors and transformers); and the glass industry uses pyrometers in areas where material temperatures change rapidly. Pyrometers are used extensively in measuring temperatures of furnaces, for hot spot detection in metal hardening processes, or in heat treatments, and in thermal mapping of temperatures in coke ovens, gas and coal furnaces, and in cement, asphalt and brick kilns.

On broadening the definition to contact-type pyrometers, additional applications include the monitoring of bearings, coatings, steam traps, electric bus bars, millings, drying and curing.

Finally, by automating the pyrometer, it can be employed in process control and regulation. It is this latter use that truly places pyrometers in the "process instrumentation" category.

ADVANTAGES AND DISADVANTAGES

Application advantages of pyrometers include:

Temperature ranges beyond thermocouple measurement capability.

Temperature measurements in thermocouple range without physical contact (remote sensing).

Temperature measurements of moving objects, work surfaces in furnaces, and detrimental atmospheres.

Response speed.

Use in extremely high-vibration and shock areas that cause short life spans for thermocouples and RTD's.

The advantages of optical pyrometers include reliability, versatility and moderate cost. Application techniques can markedly improve their capability. Principal disadvantages are weight, bulk and high cost, all associated with their automating devices.

Advantages of radiation pyrometers are good sensitivity, a high output-signal level, ruggedness, ability to read low temperatures, and economy. Principal disadvantages include sensitivity to water vapor, carbon dioxide and combustion gases in the intervening region between the pyrometer and target, and the necessity for a large target-area to detector-lens-aperture ratio. Closely related, the "ratio" pyrometer, which has good sensitivity and fast response, can be sighted on a small target.

ERRORS IN APPLICATION

The chief errors in applications are 1) the lack of experience, training and developed techniques on the part of user and 2) failure to recognize radiation characteristics of thermal target and 3) interferences between target and measuring instrument.

THERMAL MAPPING

Thermal mapping merely refers to the process of locating the points of constant temperature (contours) on a body

or surface. (These contours are analogous to the lines of constant elevation on land survey and topography maps.) Thermal mapping of an object or surface is necessary to ensure that such a condition exists, whether favorably or unfavorably. Examples include searching a boiler for hot spots that can lead to tube failure and cause an unscheduled shutdown of the plant. Such hot spots can be determined readily by a pyrometer.

EXERCISES

1. Use tables and equations in this module. If total radiation-pyrometer readout is 500°C, and the target surface is made of oxidized stainless steel, find 1) temperature (true) of target and 2) total emissive power of target.
2. Emitted energy from a switchyard circuit breaker is measured and its temperature is determined to be 445°C (emissivity of its surface is normally 0.60; the manufacturer advises that its true emissivity is 0.55). Find 1) its true temperature and 2) value of temperature error.
3. Figure 3-4-2 indicates that, for $T = 1920°K$ and $\varepsilon = 1.0$, the most probable wavelength is approximately 1.75 μ. Find the frequency associated with this wavelength.

MATERIALS

None.

PROCEDURES

(Instructor: Arrange class visit to an industrial laboratory; set up appropriate demonstration.)

1. Select target; preferably, use a portable type optical pyrometer; allow students to participate.
2. Obtain advance data on target, including temperature range and surface emissivity.
3. Obtain advance details on type of pyrometer used, including its method of calibrations and associated catalogues.
4. Discuss 1) through 3) above in class prior to site visit; have student develop basic data sheets to be used on site - this is the last module in this series on thermal measuring devices, and student should be sufficiently proficient to determine the needed data and develop the necessary tables.
5. On site, demonstrate pyrometer calibration: determine temperature of target with thermocouple; determine temperature of target with pyrometer; compare results. Record data on data table.
6. In classroom followup, analyze results, summarize results and write report.

DATA TABLE

To be developed by student.

REFERENCE MATERIALS

American National Standards Institute. "Metric Practice Guide." ANSI Standard 210.1 (E380-72). New York: American National Standards Institute, 1973.

Babcock and Wilcox Company. Steam: Its Generation and Use. New York: Babcock and Wilcox, 1972.

Considine, E.M., ed. Process Instrumentation and Controls Handbook. 2nd ed. New York: McGraw-Hill, 1974.

Harrer, J. M. and Beckerly, J.G. Nuclear Power Reactor Instrumentation Systems Handbook, Vol. 1. Springfield, VA: U.S. Atomic Energy Commission, Office of Information, Technical Information Center, 1974.

Holman, J. P. Experimental Methods for Engineers. 2nd ed. New York: McGraw-Hill, 1971.

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Moore, R. L., ed. Basic Instrumentation Lecture Notes and Study Guide - Measurement Fundamentals. 2nd ed. Pittsburgh: Instrument Society of America, 1976.

National Physical Laboratory. International Practical Temperature Scale of 1968. English version of official French text from the 13th General Conference of Weights

and Measures. London: Her Majesty's Stationery Office, 1969.

Tuve, G. L. and Domholdt, L. C. Engineering Experimentation. New York: McGraw-Hill, 1966.

TEST

Read each question carefully. Be sure your responses give the specific information each question requires. Your answers should be brief. Use the backs of the test if you need more space.

1. What is one factor that determines the quantity and spectral characteristics that a body emits?

2. What does the Stefan-Boltzmann law state about the rate of radiant energy a body emits? To what type(s) of body does the Stefan-Boltzmann law apply?

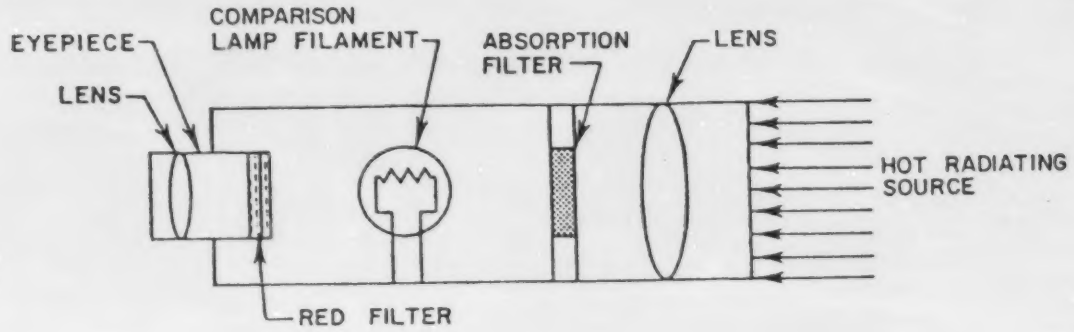
3. What is the approximate wavelength region in which thermal energy lies?

4. What is a blackbody? What is the emissivity of a blackbody?

5. What does emissivity mean? What is the reference standard for a body emissivity?

6. What effect does a steady rise in temperature have on the radiation that a body emits?

7. Below is a drawing of an optical pyrometer. Use the drawing to answer questions 7a through 7e.



a. What is the purpose of the red glass filter?

_____

b. What is the purpose of the absorption filter?

_____

c. Exactly what does the optical pyrometer measure?

_____

d. What thermally sensitive receiver element does the optical pyrometer use?

_____

e. If you were using an optical pyrometer, how would you be able to tell when a balanced condition between the lamp filament's intensity and the intensity of the incoming radiation had been achieved?

_____

8. In a radiation pyrometer, what are the factors that determine the temperature change in a receiver element?

_____

_____

9. Name two types of receiver elements or detectors commonly used in radiation pyrometers.

a. _____

b. _____

10. What is the purpose of the galvanometer used in the radiation pyrometer?

_____

11. Name the four basic types of pyrometers in commercial and laboratory use.

a. _____

b. _____

c. _____

d. _____

12. Name four performance characteristics that are especially significant when using pyrometers.

a. _____

b. _____

c. _____

d. _____

13. Briefly describe calibration of a pyrometer by the "process method".

_____

_____

_____

14. Briefly describe two principal methods of calibrating optical pyrometers.

_____

_____

_____

_____

15. List two advantages of pyrometers. (You may include optical and radiation pyrometers).

a. _____

b. _____

16. List two disadvantages of radiation pyrometers.

a. _____

b. _____

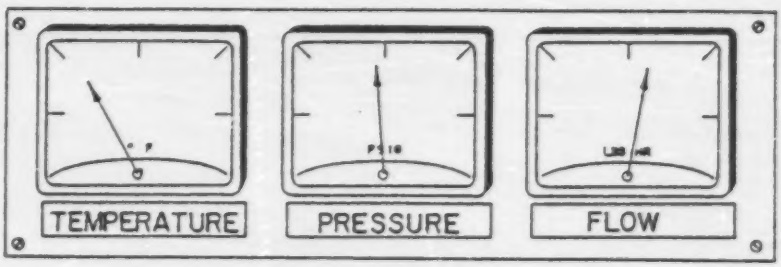
17. What are three chief errors in using or applying pyrometers?

_____

_____

NUCLEAR TECHNOLOGY

MODULE 3-5 BASIC PRINCIPLES OF FLOW MEASUREMENT



PRINCIPLES OF
PROCESS INSTRUMENTATION

COURSE 3

COURSE MODULES

COURSE 3 PRINCIPLES OF PROCESS INSTRUMENTATION

MODULE 3-1 Temperature-Sensing Devices: Glass-Bulb Thermometers

MODULE 3-2 Temperature-Sensing Devices: Thermocouples

MODULE 3-3 Temperature-Sensing Devices: Resistance Thermometers

MODULE 3-4 Temperature-Sensing Devices: Pyrometers

MODULE 3-5 Basic Principles of Flow Measurement

MODULE 3-6 Pressure-Sensing Devices

MODULE 3-7 Flow-Sensing Devices: Differential-Pressure Flowmeters

MODULE 3-8 Flow-Sensing Devices: Linear Flowmeters

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INTRODUCTION

Flow is one of the three principal process variables (flow, pressure and temperature) important to safe and efficient operation and maintenance of electrical generating power plants, conventional and nuclear. Fluid flows are used to transport thermal energy for conversion to electrical energy, and to service plant auxiliary and emergency equipment.

Rapid, accurate and direct measurement of flow and associated pressure is particularly critical in a nuclear power plant: the thermal lag, in a power reactor, between coolant flow loss and reactor damage onset is extremely short; a difference of a few tens of seconds can create an economic as well as a severe safety hazard.

Principal areas of fluid flow in a power plant include:

Boiler, or reactor, where high-temperature steam or water is produced.
Steam generators.
Turbines and condensers.
Cooling towers.
Feedwater heaters.
Condensate and pumps.
Heat and ventilation.
Other support systems.

In nuclear plants, additional and unique fluid flow requirements, such as emergency core-cooling systems and safeguard systems, require reliable and measurable fluid pressures, levels and flows.

Pressure is equally as important to efficient, safe power plant operation because fluid flow rates may be determined by measuring certain associated pressures. Also,

pressure provides a method for determining fluid levels Pressure measurements, as primary process variables, are covered in more detail in Module 3-6, "Pressure-Sensing Devices."

This module discusses:

- Basic principles and concepts of fluid and pressure, as they relate to flow.
- Relationships between flow and pressure.
- Basic principles for operation of devices used in flow and pressure measurements.
- Roles, characteristics and types of measurements required in a power plant.

The fluids of principal concern in this module are water and steam. The definitions and uses of terms commonly associated with flow and flow measurement are presented, along with their units and numerical examples.

MODULE PREREQUISITES

The student must have completed the same basic courses required for the previous modules of this series, including an introduction to nuclear technology, algebra, chemistry and electricity.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following:
   - Fluid.
   - Atmospheric pressure.
   - Absolute pressure.
   - Differential pressure.
   - Gage pressure.
   - Energy balance.
   - Velocity head (pressure).
   - Static head (pressure).
   - Volumetric flow.
   - Manometer compensation.
   - Mass flow rate.
2. Describe dynamic and static pressures as they relate to flow measurements and to Bernoulli's equation.
3. Distinguish between need for volumetric and for mass flow measurements; identify major variables influencing these types of flows.
4. Given specific values, convert pressure from psia, psig, inches of mercury and water into other conventional units and into equivalent fluid levels.
5. Describe principle of operation of a manometer; relate fluid heights to pressures measured in psia; also, relate manometer heights to flow measurements; make necessary calibration corrections.
6. Explain basic operating principles of flow and pressure-measuring devices.

FLUID MEASUREMENT OVERVIEW

Fluid flow is the controlling variable in all fluid processing industry. By being manipulated, it maintains the majority of other process variables at those values required to keep a plant producing efficiently and safely. Fluid-flow measures also are indicators of plant performance, providing records for use in operational and design analyses. Although flow is one of the most frequently measured power plant process variables, it is perhaps the most difficult to measure accurately.

To make a proper selection of fluid-flow measuring devices, to interpret instrument output and then maintain and troubleshoot installed equipment, it is necessary to understand basic principles of fluids and their flow. Also, the basic operating principles and performance characteristics of measuring devices must be understood. For such an understanding, a review of terms used in this discipline is necessary.

Density is defined as the quantity of mass per unit volume. Mass is not the weight, but the quantity of a material. The units of density are pounds mass per cubic foot (lbm/ft^3) or kilograms per cubic meter (kg/m^3). For gases, atmospheric air is the standard for comparison. The reciprocal of density is specific volume (ft^3/lbm).

Specific gravity is the ratio of the density of a substance to that of water.

Specific weight, closely associated with density, is the weight (force of gravity on a mass) of a unit volume of a substance. The units of specific weight are pounds force

per cubic foot (lbf/ft^3) or kilograms force per cubic meter (kgf/m^3).

Fluid is defined as any substance that readily changes its shape to that of its container. Both liquids and gases conform to this definition, and both are called fluids. Flow, on the other hand, is the movement of a fluid caused by some force, such as gravity or pressure, or mechanically by a pump.

Fluids are usually divided into two classes: compressibles and incompressibles. Liquids, such as water, are normally considered to be incompressible; gases, such as steam or vapors, are compressible.

The most important fluid-flow measurements made in the electrical power generation industry are those associated with a nuclear reactor. Specifically, a nuclear reactor has such a high density heat source (50 to 65 kilowatts per meter of fuel rod) that any loss of ability to remove this heat energy can result in damage to the fuel. Such damage, of course, presents a potential source of release of hazardous radioactivity.

Other typical flow measurement requirements in a nuclear power plant include:

Pressurized water reactor (PWR) primary coolant systems.
Boiling water reactor (BWR) recirculating coolant systems.
Pressurizer sprays.
Coolant pump seal injection.
Pressurized systems letdown and cooldown.
Coolant demineralizers and chemical control systems.
Boron dilution and injection systems (PWR).
Controlled releases of radioactive liquid wastes.
Primary system makeup.
Feedwater to boilers.

These examples cover a broad spanse of functional requirements important to both the measurement of fluid flow and the selection of the measuring device.

Factors influencing selection of flow-measuring devices include:

- Fluid property limitations (type, pressure and temperature).
- Applications (range, accuracy, scale and construction materials).
- Installation (size, location, connections, power requirement, orientation and access).

Various types of flowmeters may be grouped as follows:

- Volumetric.
- Mass.
- Area.
- Differential.
- Momentum.
- Electromagnetic.
- Radiation.

The units of flow come quite easily. The conventional units have been gallons, pounds and cubic feet per minute. The corresponding SI metric units (International System of Units) are liters, kilograms and cubic meters.

PRESSURE

Since pressures greatly influence the physical properties and responses of fluids, it is essential that the kinds and magnitudes of pressures be understood.

Pressure is defined as the force exerted by a fluid per unit area of confining wall:

$$\text{Pressure} = \frac{\text{force}}{\text{area}}. \qquad \text{Equation 3-5-1 (Equation = Eq.)}$$

The word "force" is emphasized because of the units of pressure used later. Pressure is conventionally measured in pounds per square inch (psi) or newtons per square meter (N/m^2). Occasionally, pressure may be measured in inches of mercury or inches of water. These latter units are more frequently used in scientific and research work but are encountered in power plants where typical pressure measurements are applied to:

Reactor primary coolant.
Steam generator steam.
First-stage turbine pressure steam.
Condenser vacuum.
Feedwater supply water.
Reheaters supply water.
Accumulator gas (nitrogen).
Primary coolant at letdown-orifice.
Pressurizer fluid.
Emergency system(s) fluids.
Suction and supply fluids of all pumps.

Also, allied with pressure is the fact that liquid levels are most often measured by pressure-sensing devices.

Basically, there are three kinds of reported, interrelated pressures (Figure 3-5-1):

Absolute.

Differential.
Gage.

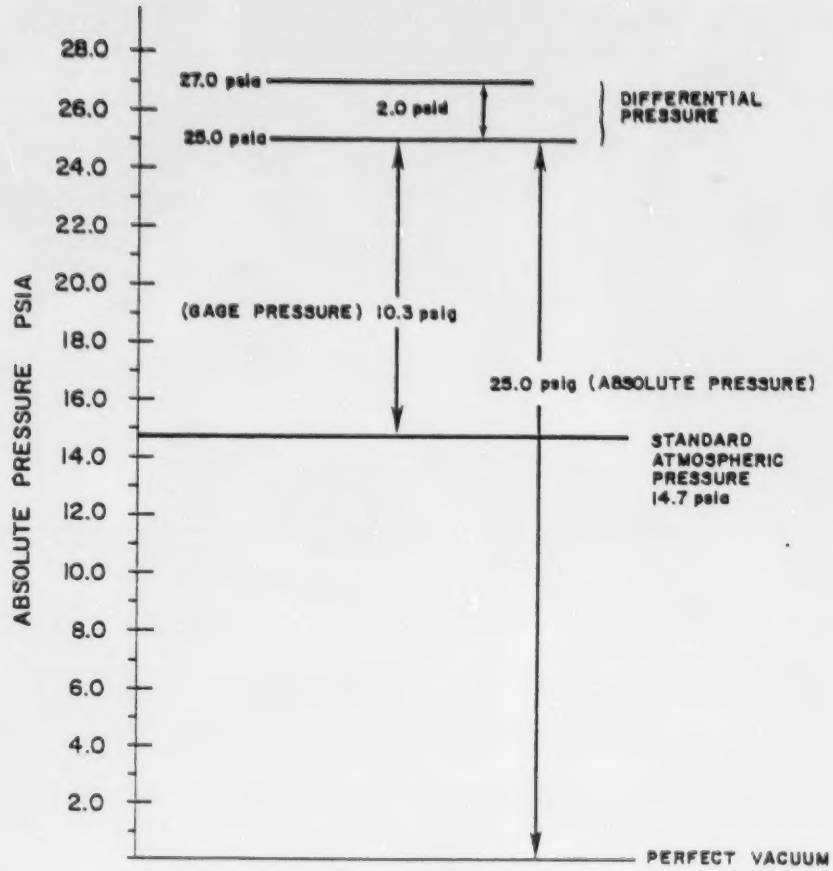

Figure 3-5-1. Kinds of pressure (examples).

Briefly, atmospheric pressure is caused by the weight of the atmosphere pressing down on an object. The standard (average) atmospheric pressure is 14.7 psi (29.92 inches of mercury). Absolute pressure (psia) is the total amount of pressure above a perfect vacuum (0.0 psia). Dif-

ferential pressure (psid) refers to the difference between any two measured pressures. Gage pressure (psig) is the measured amount of pressure above atmospheric pressure (absolute = atmospheric plus gage).

Measuring pressure is basic to measuring fluid flow and, in the case of liquids, the fluid level. Thus, to discuss flow measurements any further requires an understanding of pressures and their measurements. Such an understanding incorporates the following conversions:

1 kg = 2.205 lbs.
1 m = 3.281 ft.
1 kg/m^3 = 0.0624 lb/ft^3.
1 N/m^2 = 1.450 x 10^{-4} lbf/in^2.
1 b (bar) = 10^5 N/m^2.
1000 kg/m^3 = 62.4 lb/ft^3.
g = 9.81 m/s^2 = 32.2 ft/s^2.

PRESSURE-MEASURING DEVICES

The most widely used pressure-measuring devices are orifices and pitot tubes. The most common secondary elements are bourdon tubes.

A bourdon tube obtains an indication of pressure from the movement of a curved hollow tube, which tends to straighten out when pressure is applied. The tube is coupled to a pointer positioned over a scale (Figure 3-5-2). Normally, the bourdon tube is curved through about 200 to 300 degrees of arc. In some bourdon tube instruments, a flat, hollow tube is twisted instead of curved. In either case, applied pressure causes a movement in the tube that

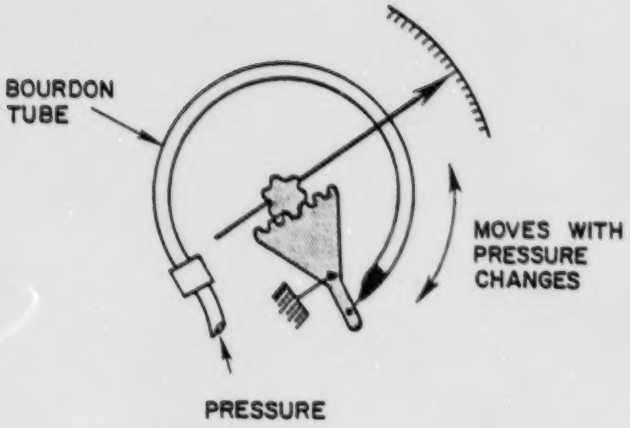

Figure 3-5-2.
Bourdon pressure tube.

is used to indicate the amount of applied pressure.

A bourdon gage can be used to measure gage pressures (psig), vacuum pressures, compound pressures and differential pressures. For psig and vacuum measurements, the gage is connected to the source and a reading is obtained on the gage dial.

The bourdon tube is a widely used pressure-sensing device because it can be used to measure the pressure of almost any fluid.

LEVEL-MEASURING DEVICES

"Level" is the position of the interface between phases, where phases are liquid/gas, solid/gas or immersible liquid/liquid. Also, "level" is a measurement of volumetric quantity and, less rigorously, gravimetric quantity.

Thus, level measurements are treated from two viewpoints: that of defining the position of an interface and that of indirectly measuring volume.

For power plants, level measurements must be compensated for density changes due to increased temperatures. For example, in the pressurizer, the true mass level is only about one-half of the indicated volumetric level. Because of this, an RTD is used to make temperature compensations to a console readout so that true level is indicated in terms of mass.

It is only logical that levels be defined in terms of pressure. The simplest method of measuring levels is the installation of properly calibrated pressure gage at the point of minimum level. (Types and forms of level sensors are discussed in more detail in Module 3-6, "Pressure-Sensing Devices.")

The types of level measuring devices most commonly used are visual standpipes, floats and pressure-gage transducers.

VACUUM-MEASURING DEVICES

Vacuum measurements are actually pressure measurements made at below atmospheric pressures (pressure-vacs). The most important measurement is the condenser vacuum at the tail of the steam turbine (Figure 3-5-3). Here, devices using bellows and manometers measure from 14.7 psi (at zero vacuum) down to 0.1 inches of water.

In a flow of air or in slight reductions of building pressures (below atmosphere) to ensure inleakage of air (containment or confinement), vacuum is measured by an in-

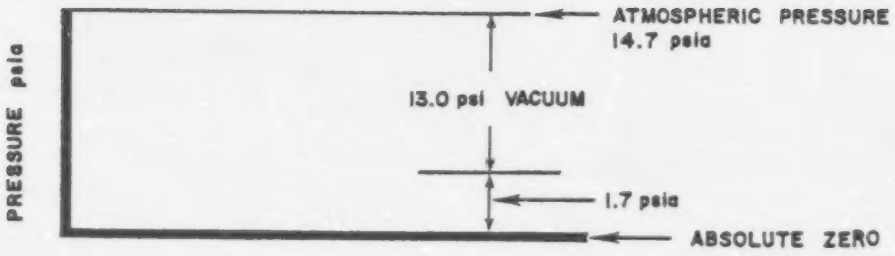

Figure 3-5-3. Vacuum pressure.

verse bourdon tube process. This vacuum (or differential pressure) is usually measured in inches of water below ambient (0.1 - 0.8).

Absolute pressure, in psia, may be determined as follows:

$$P_{abs} = P_{atm} + P_{psid} \qquad \text{Eq. 3-5-2}$$
$$= 14.7 \text{ psia} + (-13.0 \text{ psia})$$
$$= 1.7 \text{ psia.}$$

Measurements of air flow through filters and gaseous radiation monitors require high sensitivity; therefore, inclined low-pressure U-tube manometers are used (Figure 3-5-4). In this kind of manometer, a small vertical difference in levels is magnified on the longer, inclined scale, creating a greater sensitivity to minute variations in pressure. In most applications, the inclined-tube measures differentials in inches of water; a 33.9-foot column of water is equivalent to one standard atmospheric pressure, or 14.7 psi.

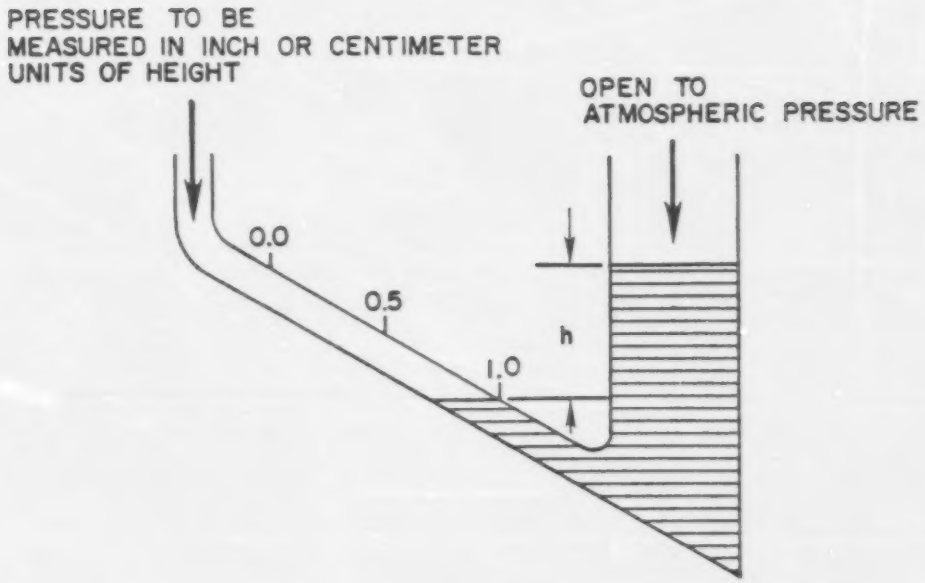

Figure 3-5-4. Inclined-tube manometer.

Pressures expressed in the SI (metric) units are yet to become commonplace; however, conversions from conventional engineering units are progressing rapidly and on a determined basis:

$$\text{Pressure} = \text{Force/Area} = \text{Newtons/(Meters)}^2 = N/m^2.$$

Expressing N in terms of kg, m and s ($1\ N = 1\ kg\ m/s^2$), gives

$$1\ N/m^2 = 1\ kg/ms^2 \quad \text{or}$$

$$1.0\ N/m^2 = 1.45 \times 10^{-4}\ lbf/in^2 \quad \text{or}$$

$$10^5 N = 10^5 \text{ Pascals} = 1 \text{ bar}$$

EXAMPLE

1.0 Atmosphere = (101325 Newtons/m^2)
= 101325 N/m^2
= 101325 Pa.

Therefore,
14.7 psi = 1 atmosphere
= 101325 Pa
= 29.92 in Hg
or 1.0 psi = 6894 Pa.

EXAMPLE
Given: Steam condenser pressure is 28.15 inches of Hg, vacuum.

Find: Absolute pressure in SI units.

Solution:

$$\frac{29.92 - 28.15}{29.92} (14.7) = 0.87 \text{ psia}$$
$$= 5998 \text{ Pa.}$$

BASIC PRINCIPLES OF FLOW MEASUREMENTS

To understand fluids in a specific system, it is necessary to be familiar with some of the elementary charac-

teristics of fluids while they are in motion or static (not moving).

FLUID FLOW

Significant flow characteristics include:

- Volume and mass flow.
- Steady and unsteady flow.
- Mass force and energy changes that occur in flow.

The latter is typically referred to as the "law of conservation of mass, energy and momentum." The conservation of mass is easily understood; e.g., the amount of fluid entering a pipe (assuming no leaks) must equal that exiting from the pipe.

FLUID STATICS

Pressures are transmitted by fluids to all parts of contact. This phenomenon, based on Pascal's law for static fluids, states that the pressure on a particle or element of a static nonflowing fluid is the same in all directions, neglecting pressure due to the weight of the fluid itself.

A typical example of this law would be an inflated tire. Air pressure is the same everywhere in the tube. A useful application of this law is the hydraulic piston used to lift a car at a service station. A heavy car can be lifted with a reasonably low-pressure system (Figure 3-5-5).

Assume two pistons of different size are connected as shown. By Paschal's law, pressure P is equal throughout the system. If the downward force on piston A is 600 lbf; the

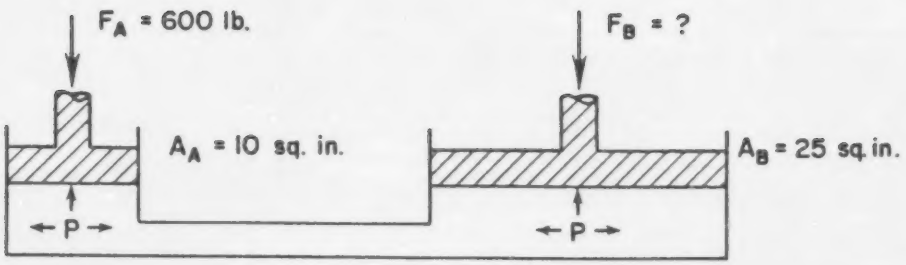

Figure 3-5-5. Hydraulic system.

calculated pressure exerted on the fluid by piston A is:

$$P_A = \frac{F_A}{A_A} = \frac{600 \text{lbf}}{10 \text{ in}^2} = 60 \frac{\text{lbf}}{\text{in}^2} = 60 \text{ psi.}$$

Because P is constant,

$$P_B = \frac{F_B}{A_B}$$

therefore

$$\begin{aligned} F_B &= P_B A_B \\ &= P_A A_B \\ &= 60 \frac{\text{lbf}}{\text{in}^2} \times 25 \text{ in}^2 = 1500 \text{ lbf.} \end{aligned}$$

Under normal plant conditions, the fluid in a power system is most often under pressure and completely fills the pipes, tanks and assemblies of the systems. Its pressure is due in part to the force of gravity or weight of the

fluid (statics), in part to forces applied externally by pumps or compressors, and in part to the result of adding energy to the fluid (e.g., water to steam).

VELOCITY AND MASS FLOW RATE

The mass of fluid that passes a given point in a fluid system in a unit of time is referred to as mass flow rate - the rate (or speed) at which fluid moves past a particular point in the system. Mass and velocity of flow are often considered together. With other conditions unaltered - that is, with volume of input unchanged - the velocity of flow increases as cross-sectional area (size) of a pipe decreases; inversely, the velocity of flow decreases as cross-sectional area increases. In an open river or stream, flow velocity generally is slow through wide sections and rapid through narrow sections, even though the volume of water passing each part of the stream is the same. The equation for this continuity of mass is expressed as follows:

$$V_A A_A \rho_A = V_B A_B \rho_B \qquad \text{Eq. 3-5-3}$$

where

V = average velocity of fluid.
A = cross section of pipe
ρ = density of fluid.

COMPRESSIBILITY AND TEMPERATURE EFFECTS

If fluid density is constant (i.e., if there are no temperature or compression effects, such as expansion or contraction), then the mass equation of continuity is equivalent to the volumetric equation of continuity:

$$A_A V_A = A_B V_B.$$

Liquids are essentially noncompressible (however, they are affected by temperature). Liquids can be only slightly compressed, even under extreme pressures. For example, if 100 psi is applied to a body of water, the original volume will only decrease 0.03 percent.

The effects of temperature are not as neglibile. For example, the density of water in an operating reactor's coolant system is about half its density at room temperature. Since heat-transfer capabilities and energy carrying capacities of coolants in power plants are related to fluid mass rather than volume, it is important to be able to measure mass flow or to be capable of correcting volumetric flow.

BERNOULLI'S ENERGY EQUATION

With the previous discussion in mind, the first practical consideration of fluid-flow measurement requires the stating of an energy balance. Bernoulli developed an energy equation for an incompressible fluid with a constant density. In a frictionless flow of fluid through a pipe (Figure 3-5-6), three significant components are measured in terms of "heads" (equivalent weights of columns of fluid in units of feet or

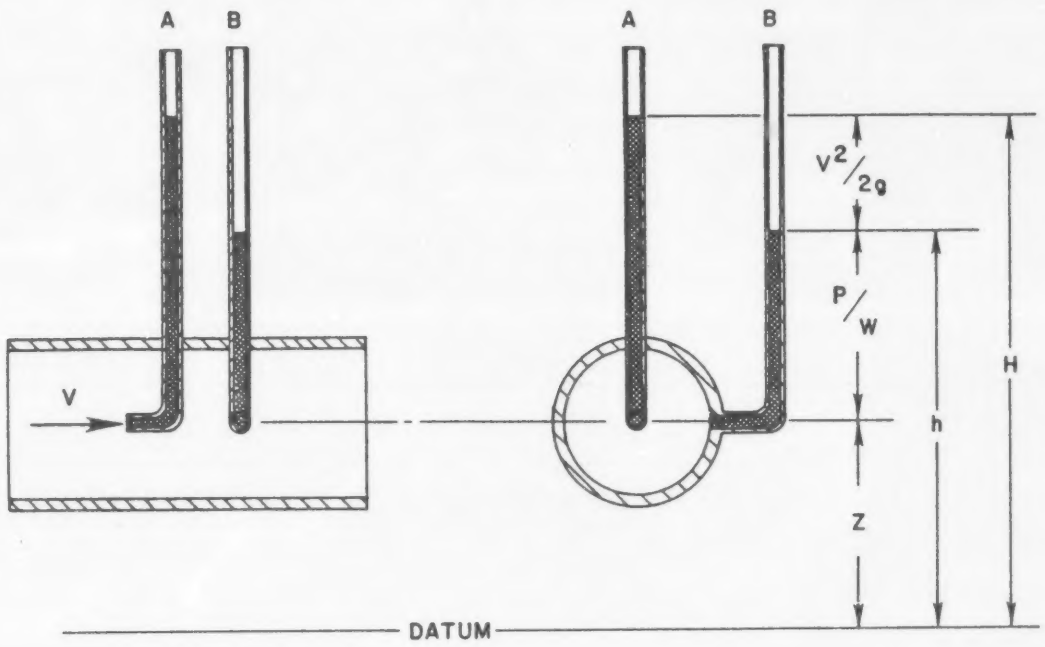

Figure 3-5-6. Total and static heads for fluid flow.

meters). These columns are defined as velocity head (kinetic head), pressure head and elevation head (potential energy of the fluid). For instructional purposes, they are combined to illustrate Bernoulli's energy equation for the flow of incompressible fluids:

$$\frac{V^2}{2g} + \frac{P}{\rho g} + Z = H \qquad \text{Eq. 3-5-4}$$

where

H = constant (called total head or total pressure), usually measured in feet of fluid.

$\frac{V^2}{2g}$ = velocity head, with units of $(\frac{ft}{sec})^2$ $(\frac{sec^2}{ft})$ or feet.

$\frac{P}{\rho g}$ = pressure head, in feet.

Z = elevation head (height of fluid above a datum) in feet.

The term ρg is the gravity force (weight per unit volume), i.e., specific weight. Thus, $\frac{P}{\rho g}$ may be written as $\frac{P}{W}$, in units of feet; $\frac{P}{W}$ represents energy per kg of fluid needed to raise its pressure by P (where W = weight).

It is sometimes convenient to refer to the sum of the terms $(\frac{P}{W} + Z)$ as the static (piezometric) head. In the energy equation, internal energy of the fluid is assumed to be constant. Module 5-2, "Pressurized Water Reactor (PWR)," discusses this aspect in terms of energy transported in a power plant.

Tubes inserted in a pipe (Figure 3-5-6) are identified as A and B. Tube A is bent so that its open end faces directly upstream (perpendicular). The fluid stream striking this open end is brought to rest (stagnant). This tube is called a pitot tube, measures both the velocity head and the pressure head (i.e., the total flow head).

Tube B, inserted in the pipe wall so that its open end is flush with the inner wall, causes no disturbances to flow. Fluid flows past the open end of this static tube without deceleration, which allows it to record static (piezometer) head.

The level in Tube A (total head of fluid above datum)

exceeds the level in Tube B (representing static head of the fluid) by an amount equal to the velocity head.

Note: All heads are convertible to pressures; i.e., the velocity head represents velocity pressure; the static head represents static density:

$$\text{Pressure} = \left(\frac{V^2}{2g}\right)(\rho g) \qquad \text{Eq. 3-5-5}$$

$$= \left(\frac{\text{ft}^2 \times \text{sec}^{-2}}{\text{ft} \times \text{sec}^{-2}}\right)(\text{lbm} \times \text{ft}^{-3} \times \text{ft} \times \text{sec}^{-2})$$

$$= (\text{ft})(\text{lbm} \times \text{ft}^{-2} \times \text{sec}^{-2})$$

$$= \frac{\text{lbm}}{\text{ft} \times \text{sec}^2}$$

$$\text{also lbf} = \text{lbm} \times \frac{\text{ft}}{\text{sec}^2}$$

$$\therefore \text{lbm} = \frac{\text{lbf} \times \text{sec}^2}{\text{ft}}$$

$$= \frac{\text{lbf} \times \text{sec}^2 \times \text{ft}^{-1}}{\text{ft} \times \text{sec}^2}$$

$$= \frac{\text{lbf}}{\text{ft}^2}.$$

Friction, which is always present, must be considered. In practical cases, loss of head or pressure by friction is caused by the fluid flow. This loss is subtracted from the velocity head and added to the static head.

If one end of the pipe (Figure 3-5-6) were higher than the other, the elevation head, Z, would be the difference, in feet, between any two points of measurement.

MEASUREMENTS AND CHARACTERISTICS

A wide variety of instruments and techniques are used in power plants to measure quantity and rate of fluid flow, and its pressure (or levels). Because power plants principally measure liquids, particular attention must be given to their characteristics and measurement.

BASIC MEASUREMENTS AND UNITS

The need for accuracy in fluid measurement depends on the use of the information, and on the kind of system being considered. For example, the flow rate of primary coolant water through a PWR system is essentially constant, with the rate based on operational and safety requirements. Special tests of the planned final configuration of the pressure vessel, pumps and piping system are made to confirm the fixed flow rates before the plant is built. Then, after the plant is built, the principal concern is that, in the event of a flow rate drop of more than (say) 10% below designed rate, the reactor shuts down. For this, a differential (relative change) flow rate is the only flow measurement required for safe operation. In other parts of the plant, however, accurate flow rates may be required to ensure a proper supply of fluids to specific components, such as pumps for feedwater to the steam generator, based on turbine steam demands.

Flow measurements in this latter case must not only be accurate but also must be immediate and responsive to the control system's input to the pump.

Flow rates are expressed in both volumetric and weight

units per unit time. Gases are generally measured by cubic feet per minute (or hour), steam in pounds per hour and liquids in gallons per minute (or hour). The most accurate method of measuring liquid flow would be by weighing the quantity of flow; remember, specific weight, density and specific volume all change with temperature change in the fluid. Conversion between volumetric flow and weight (mass) flow may be expressed simply:

$$m = \rho Q \qquad \text{Eq. 3-5-6}$$

where

ρ = density of fluid.
m = mass flow rate.
Q = volumetric flow rate.

The closed cycle systems in a power plant make the above method impractical. Thus, flows must either be measured by 1) application of the principle of "conservation of mechanical energy" through the conversion of a fluid's velocity to the various types of pressure heads discussed previously, or 2) by mechanical displacements induced by flow, with such devices as paddles, floats or turbines. Categorically, all the above devices are called flowmeters.

CLASSIFICATION OF DEVICES

Typically, various types of flowmeters may be grouped as follows:

Volumetric.
Area.

Differential.
Momentum.
Electromagnetic.
Radiation.

From the above, there is usually one device that is most appropriate for a particular process instrumentation need. Selection of a specific meter depends on required accuracy, operating environment, expense and durability.

A basic consideration of flow sensing (Module 3-1, "Temperature-Sensing Devices: Glass-Bulb Thermometers") is that all flowmeters consist of two parts: 1) primary element; i.e., the element in contact with the flowing fluid, and 2) secondary element, which translates the interaction into numbers and indicates (or otherwise displays or records) the desired information.

Quantity measurements, by mass or volume, are usually accomplished by counting successive isolated portions of the fluid, whereas rate measurements are inferred from the effects of the fluid rate on pressure, force, heat transfer, flow area, and so on.

Sensors for power plants are usually divided into two groups: 1) differential pressure or inferential flowmeters, and 2) linear flowmeters. Very simplified models of these meters are discussed in this module, while their basic principles of operation, specific applications and other details are covered in later modules in this course.

MANOMETERS

Because most of the common pressure-measuring devices can be readily adapted to measure either liquids or gases, or both, they are described simply as fluid-measuring de-

vices. Similarly, the flow of fluid can be related to its velocity and static heads (pressures). In fact, the change in pressure from one point to another is directly proportional to the velocity squared (assuming constant velocity). This principle is used in all pressure-measuring devices to determine velocity.

One of the simplest and most dependable devices for measuring pressure and pressure differentials is the manometer, a device that measures pressure by comparing it to the height of a static column(s) of liquid. There are many types of manometers:

Absolute pressure gage.
Fixed-cistern barometer.
U-tube.
Well-differential.
Inclined-tube
Ring-balance.
McLeod gage.

The simplest manometers are those in which a liquid column is balanced against pressure. These devices consist of a vertical tube tapped into the top of a pipe containing a liquid. The liquid rises in the tube until the weight of the column balances the pressure in the pipe: pressure = weight x height of the liquid column.

A U-tube (Figure 3-5-7) manometer has one leg connected to the pressure to be measured while the other leg is closed and evaucated. This device measures absolute pressure. If the second leg of the U-tube is connected to another point in the process, such as before or after an air filter, a differential pressure is measured.

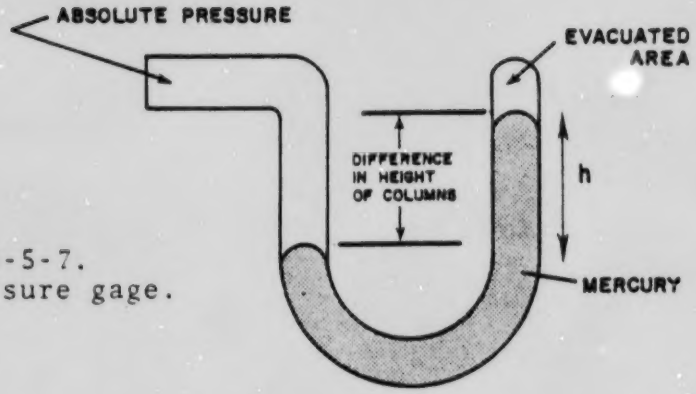

Figure 3-5-7.
Absolute pressure gage.

In well-type manometers (Figure 3-5-8) the liquid remains in the reservoir until a pressure is applied. Then the liquid rises in the tube to indicate the amount of pressure being applied.

Most manometers have a scale attached to measure variations in liquid levels. The basic relationship for all manometers is that there is a static pressure balance between the two columns of liquid.

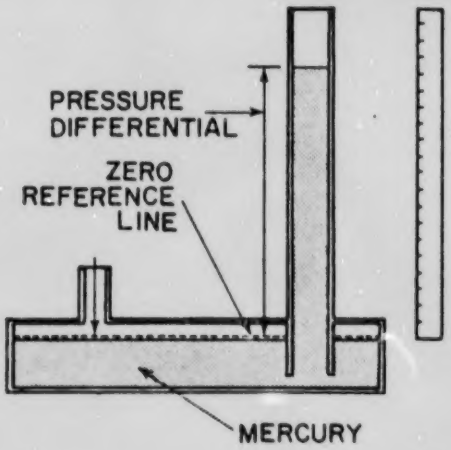

Figure 3-5-8.
Well-type manometer.

U-tube and well-type manometers can be used to measure differential pressures from about 0.5 to 50 inches of mercury pressure. The pressure indications of most manometers are designed for specific applications, but they operate and obtain pressure indications in the manner just described.

Manometers contain various liquids, such as water, alcohol, mercury, bromide compounds, organics and other special fluids.

CALIBRATION OF MANOMETERS

The basic method used to calibrate a manometer is to equate the head (height) of the column's fluid to the equivalent pressure it exerts. To obtain the desired accuracy, its fluid density, temperature and viscosity must be known. To minimize error, use standard fluids with known densities and viscosities. Also, add the appropriate temperature correction to the indicated height.

ACCURACY

The accuracy of a manometer can be optimized by insuring clean intertube surfaces and pure fluids, and by minimizing surface tension of the fluid and by obtaining a steady state and streamlined flow of the fluid being measured.

The sensitivity of a manometer can also be increased by inclining the manometer's tube. In addition, the use of

low-specific gravity manometer fluids, optical magnifications and level-sensing devices can enhance accuracy.

EXERCISES

1. A manometer reads 10 inches of mercury (29.92 inches of Hg = 14.9 psi). Find the pressures, (a) psig (b) psia, corresponding to the 10 inches of mercury. (Use Table 3-5-1.)
2. A steam boiler pressure gage reads 2590 psi. Find its absolute pressure, expressed in psid, Hg and feet of water. (Use Table 3-5-1.)
3. The specific weight of a particular oil is 48 lbf per cubic foot. A manometer filled with this oil measures the differential pressure across a boiler fuel-oil feed nozzle. Find the pressure difference if the manometer fluid is displaced 8 inches.
4. Given: 20°C coolant water flowing at 10 meters per second while the reactor pressure vessel is at 1000 psig. Find: Total head of system at the coolant pump, which is located 20 meters below the pressure vessel's fluid level.

TABLE 3-5-1

DENSITY VERSUS TEMPERATURE AND PRESSURE FOR WATER

TEMP. (°F)	DENSITY ρ (lb_m/ft^3)		
	Sat. liquid	1,000 psia	2,000 psia
32	62.422	62.637	62.846
40	62.422	62.657	62.854
60	62.344	62.539	62.755
80	62.189	62.383	62.586
100	61.996	62.185	62.371
120	61.728	61.920	62.104
140	61.387	61.576	61.767
160	61.013	61.200	61.395
180	60.569	60.753	60.953
200	60.132	60.314	60.511
210	59.809	60.006	60.205
220	59.630	59.830	60.031
240	59.102	59.305	59.506
260	58.514	58.727	58.938
280	57.937	58.156	58.377
300	57.307	57.537	57.767
320	56.657	56.883	57.136
340	55.960	56.211	56.465
360	55.218	55.463	55.710
380	54.466	54.720	55.012
400	53.648	53.903	54.218
420	52.798	53.042	53.396
440	51.921	52.154	52.546
460	51.020	51.230	51.661
480	50.000	50.191	50.659
500	49.020	49.097	49.618
520	47.847	.....	48.527
540	46.512	.....	47.181
560	45.249	.....	45.905
580	43.860	.....	44.492
600	42.373	.....	42.913
620	40.486	.....	40.950

MATERIALS

Metal section with either orifice or venturi 1/2 the diameter of the tubing.
Rubber tubing.
Valve compatible with rubber tubing.
Two low-pressure gages.

PROCEDURES

1. Set up the tubing arrangement shown in Figure 3-5-9. Be sure gages are at the same height and that water flow is horizontal. Inlet valve should be completely open; outlet valve should be closed.

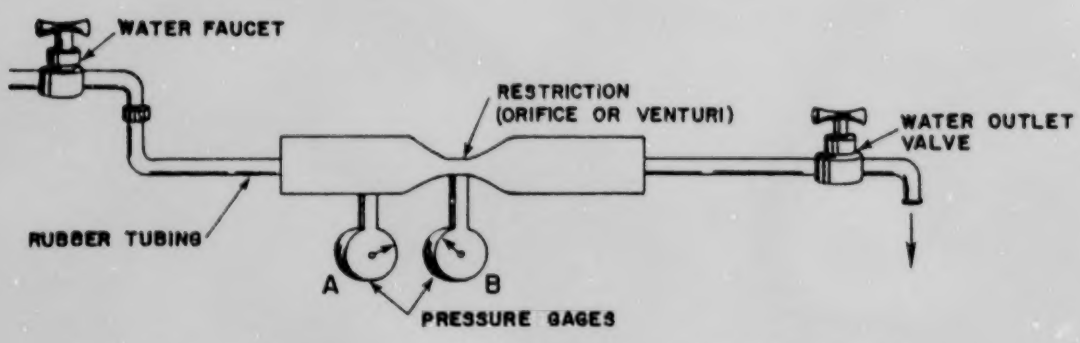

Figure 3-5-9. Experimental tubing arrangement.

2. Open outlet valve to allow lowest rate of flow at which a differential pressure can be noticed between gages A and B.

3. Record differential pressure on Data Table 3-5-1.
4. Increase flow, in small increments, recording differential pressure at each flow rate.
5. Note effect of increasing flow through the system on differential pressure.

DATA TABLE

DATA TABLE 3-5-1

	Pressure Gage A	Pressure Gage B	Differential Pressure
lowest flow			
highest flow			

American National Standards Institute (ANSI). Metric Practice Guide, ANSI Standard Z210.1. New York: American National Standards Institute, 1973.

Bureau of Naval Personnel. Fluid Power. From the Navy Training Course. Washington, DC: Department of Defense, 1970.

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Holman, J.P. Experimental Methods for Engineers. 2nd ed. New York: McGraw-Hill, 1971.

Lottes, P.A. The Reactor Handbook, Vol. 2. From USAEC Report AECD-3646. Washington, DC: U.S. Government Printing Office, 1955.

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Oak Ridge National Laboratory (ORNL). Reactor Operator Study Handbook, Vol. 5, Instrumentation and Control, ORNL-TM-2034. Oak Ridge, TN: ORNL.

TEST

Read each question carefully. Be sure your responses give the specific information each question requires. Your answers should be brief. Use the backs of the test if you need more space.

1. Why is rapid, accurate and direct measurement of flow and associated pressure critical in a nuclear power plant?

2. Name five principal areas of fluid flow in a power plant.

   a.

   b.

   c.

   d.

   e.

3. What is a fluid? What are the classes of fluids?

4. What is flow? What are the metric units of flow?

5. What factors influence selection of flow-measuring devices?

6. Define pressure.

7. Name three typical pressure measurement applications in power plants.

   a.

   b.

   c.

8. Name and define three kinds of reported, interrelated pressures.

a. _____

_____

b. _____

_____

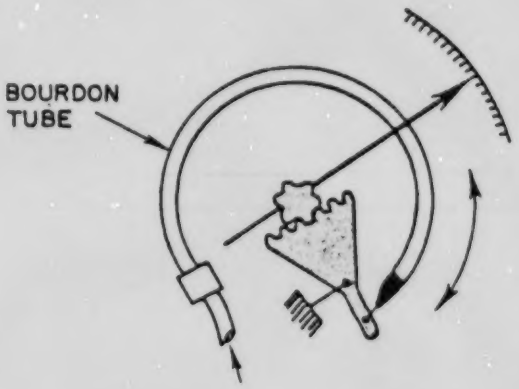
c. _____

_____

9. What is atmospheric pressure?

_____

10. Below is a sketch of a Bourdon tube. Questions 10a through 10c pertain to the Bourdon tube.



a. How does the Bourdon tube measure pressure?

_____

b. Describe the movement of the tube when pressure is applied.

_____

c. Why is the Bourdon tube widely used to measure pressure?

_____

11. Give three definitions of "level".

_____

_____

_____

12. Name one commonly used type of level measuring device.

_____

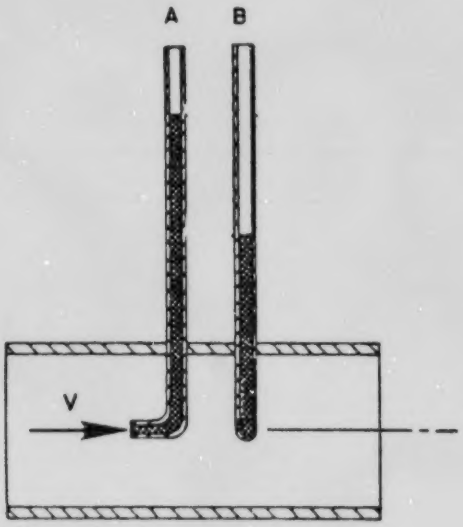
13. How are vacuum measurements related to pressure measurements?

14. What is mass flow rate?

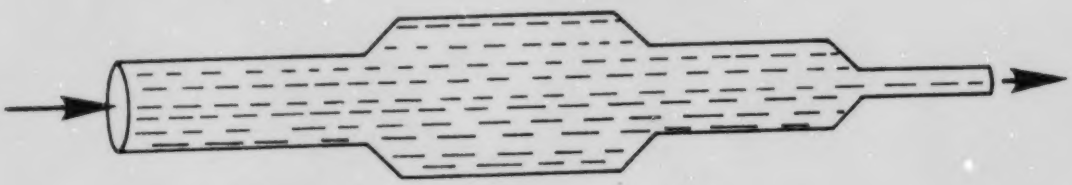
15. If a pump moves fluid at a velocity head of 25 feet, how many feet would it raise a column of water?

16. What is the weight of water at the base of a column, that is connected to a system at 100 units psia static pressure?

17. In the sketch of the Pitot tube below, label the sections of columns A and B that represent velocity head (V).



18. Describe the mass flow rate as a liquid moves through the pipe sketched below. Assume that the volume of input remains unchanged.



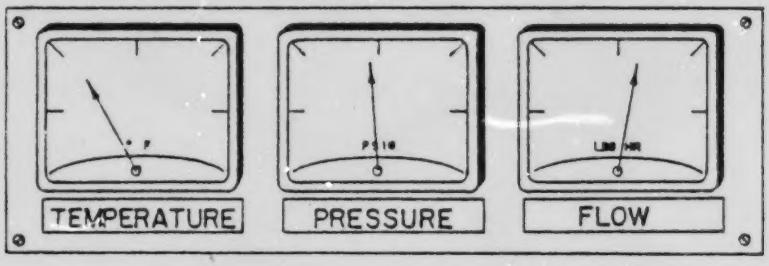
19. Name two types of flow meters.

20. Sketch a simple manometer. Briefly describe how the manometer meausres pressure.

21. What is the most accurate (although sometimes not practical) way of measuring flow? How is volumetric flow converted to mass?

NUCLEAR TECHNOLOGY

MODULE 3-6 PRESSURE-SENSING DEVICES



PRINCIPLES OF
PROCESS INSTRUMENTATION

COURSE 3

COURSE MODULES

COURSE 3 PRINCIPLES OF PROCESS INSTRUMENTATION

MODULE 3-1	Temperature-Sensing Devices: Glass-Bulb Thermometers
MODULE 3-2	Temperature-Sensing Devices: Thermocouples
MODULE 3-3	Temperature-Sensing Devices: Resistance Thermometers
MODULE 3-4	Temperature-Sensing Devices: Pyrometers
MODULE 3-5	Basic Principles of Flow Measurement
MODULE 3-6	Pressure-Sensing Devices
MODULE 3-7	Flow-Sensing Devices: Differential-Pressure Flowmeters
MODULE 3-8	Flow-Sensing Devices: Linear Flowmeters

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Waco, Texas 76710

2. Outline a review of specific functional types of pressure sensors, detailing elastic elements and strain gages.
3. Describe transducers as means of transmitting pressure signals to process control circuits and a control console.
4. Describe calibration technique for pressure elements.
5. Calculate fluid flow and level measurements, based on pressure data.
6. Draw basic diagrams of typical mechanical and manometer-type pressure-sensor devices, along with simplified transducers.
7. Hook up, calibrate and operate a manometer and a bourdon gage; plot calibration curve and calculate gage error, based on laboratory data.

PRESSURE MEASURING DEVICES

Pressure sensing is required in coolant loops, waste systems, and in containment and radiation control systems. Most process information is displayed on meters or recorders, either locally or remotely, in a control room. Pressures are also used as inputs to process controllers, plant protection systems and computers.

Pressure-measuring devices generally fall into two major categories: manometers and mechanical gages. A mechanical gage or element (also referred to as an "elastic pressure element") includes diaphragms, bellows and bourdon tubes.

These sensor devices respond to a system pressure and generate a measurable physical quantity, such as a force or movement (displacement). Manometers, on the other hand, are the familiar liquid columns in which density and height of liquid are correlated to measure pressure.

Special types of mechanical elements include 1) strain gages and 2) piezoelectric sensors. A strain gage consists of a fine wire or array of fine wires bonded into an assembly for mechanical strength. Under an applied stress, these wires stretch, resulting in an increase in electrical resistance, which can be made to be directly proportional to the imposed "strain" (pressure).

A piezoelectric device is similar to a strain gage, except that a crystal replaces the wires, and pressure generates a small electrical voltage.

Devices for measuring vacuums associated with power plant operation are also of the mechanical and manometer

types. In addition, several electrical and electronic systems are available.

Since level is, by definition, head or pressure, most of the above categories of pressure-measuring devices are also used in level sensing.

Pressure-measuring devices take various forms, depending on the magnitude of the pressure, desired accuracy and environment, location and similar conditions. Table 3-6-1 provides a quick reference to pressure-sensing devices, including their abilities and accuracies.

Applications of conventional pressure-measuring devices to nuclear power plants require that they have high reliability, tolerance to high radiation fields, exceptional accuracy in many applications and minimum drift. The range of applications is similar for fossil plants, and the application of specific devices is generally the same as in other process facilities. For example, differential-pressure measurements of fluid flow are found in:

Steam lines and off-gas systems.
Elastic devices on the discharge and suction primary.
Feedwater and safety injection pumps.
Static-pressure points in (for fluid level) accumulators and pressure vessels.
Pneumatic head measurement points on valve controls.
Instrumentation air and diesel air start motors.
Cylinder pressure points on hydraulic snubbers and hangers.

Furthermore, oil pressure measurements, fuel-line pressure gages and similar uses (with conventional components and systems) find universal employment. (Specific applications are discussed in more detail in a later section.)

TABLE 3-6-1
REFERENCE DATA ON PRESSURE-MEASURING DEVICES

CLASS	TYPE	Optimum Range*	Accuracy†
U-Tube Manometer	Glass—mercury	0.5-50"Hg	0.02"
	Glass—water	0.5-100"H_2O	0.02"
	Glass—two-liquid	0.01-1"H_2O	0.5%
	Float, electric, etc.	0.5-50"Hg	0.05"
	Multiple-tube	10-100"Hg	0.5%
Single tube Manometer	Vertical—open top	2-100"Hg	0.02"
	Compression manom.	vac.-200 psi	1%
	Open-cistern, vac. gage	0-30"Hg	0.02"
	Mercurial barometer	Atmospheric	0.01"
	do., photocell servo	Atmospheric	0.005"
	Abs. pressure gage	0-100" Hg abs.	0.005"
	Inclined-tube	0-4"H_2O	0.005"
Micromanometer	Null method, etc.	0.001-20"H_2O	0.05%
Liquid col. & plunger	Mercury	50-5000 psi	
Weight loaded piston	Dead Weight	to 100,000 psi	0.1%
	Fluid pressure scale	50-8000 psi	0.2%
	Pendulum	100-8000 psi	0.2%
	Automatic balance	200-1000 psi	
Liquid-sealed bell	Oil sealed	0.1-10"H_2O	1%
	Mercury sealed	0.1-1.5"Hg	1%
Tilting	Ring, etc.	0.1-10"Hg	2%
Tube-spring	Single Bourdon	10-30000 psi	2%
	do., elec. trans.	10-3000 psi	2%
	do., pneu. trans.	10-3000 psi	2%
	do. "Inspector's"	10-5000 psi	0.5%
	Double Bourdon	50-800 psi	2%
	Helical	5-500 psi	1.5%
	Spiral	10-1000 psi	1.5%
Diaphragm (Metallic)	Unloaded, flat	1-200 psi	1.5%
	Unloaded, corrugated	0.5-50 psi	2%
	Spring-loaded	2-200 psi	1%
	do., strain-ga. trans.	50-1500 psi	1%
	do., pneu. trans.	vac.-300 psi	0.5%
Membrane (leather, fabric, plastic, etc.)	Spring-loaded	0.2-100"H_2O	1.5%
	do., elec. trans.	0.1-50"H_2O	1.5%
	do., pneu. trans.	0.1-40"H_2O	1.5%

CLASS	TYPE	Optimum Range*	Accuracy†
Bellows	Unloaded	1-100"H_2O	2%
	Spring-loaded	0.5-200 psi	2%
	do., elec. trans.	0.5-50 psi	1%
	do., pneu. trans.	0.1-100 psi	1%
	Pendulum-loaded	10-200"H_2O	2%
Capsular spring	Unloaded	1-50"H_2O	3%
	Aux. spr. loaded	0.5-100 psi	2%
	Null method	Atmospheric	0.1%
	Aneroid barometer	Atmospheric	0.2%
Electrical	Carbon pile, etc.	50-200 psi	2%
	Crystals	100-20,000 psi	2%
	Electromagnetic	5-10000 psi	2%
	Manganin, etc.	1000 atm up	3%
	VACUUM	MICRONS	
Liquid column (compression manom.)	Laboratory McLeod	0.01-2000	2%
	Industrial McLeod	0.1-100,000	
Viscosity or molecular	Strictly lab. types	0.0001-100	
	Field (milit. research)	1-760,000	
	Industrial	10-750,000	
Radiometer	Knudsen	0.0001-1	
	Aluminum vane	0.00001-1	
	Aluminum leaf	0.1-100	
Conductivity	Thermocouple	1-500	
	Resistance (Pirani)	1-250	
	do., semiconductor	1-1000	
	Wire length	0.01-100	
Ionization	Thermionic	0.00001-10	
	do., Aurosa.indic.	5-2000	
	Cold (Phillips)	0.01-1000	
	do., glow indic.	0.1-1000	
	Alpha-particle	1-10,000	
Elastic-member	Unloaded	10-10,0000	

PRESSURE SYSTEMS (SENSING/TRANSMISSIONS)

Characteristics of the devices mentioned above were covered in a previous module; however, additional descriptions of the more specialized devices are appropriate.

Liquid Column

Basically, liquid columns are used to measure absolute and differential pressures. Inclined-tube differential manometers (Figure 3-6-1) are used principally to measure small pressure drops across containment and auxiliary building filters and zone pressures and air flows between rooms and areas.

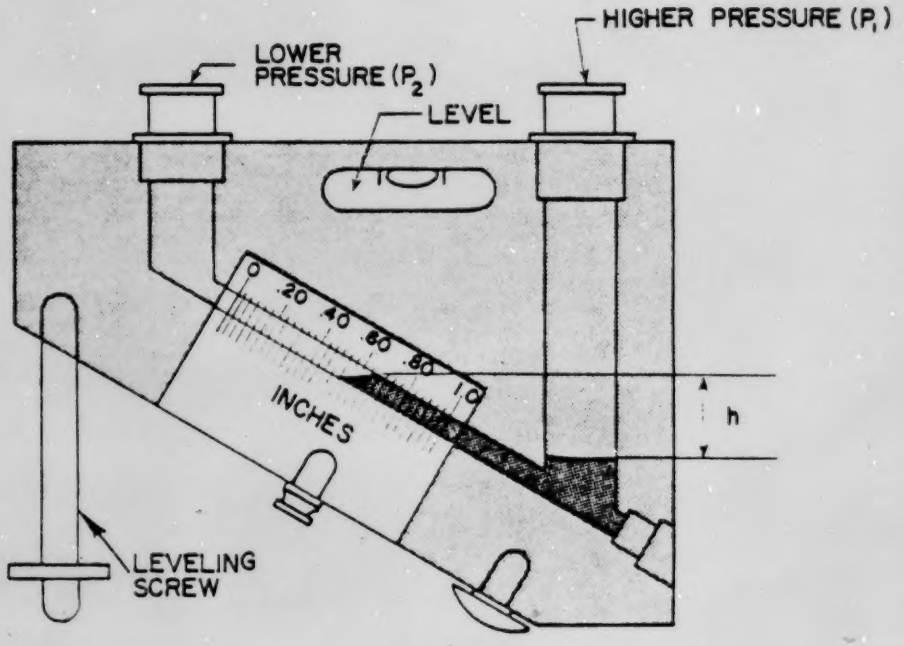

Figure 3-6-1. Inclined-tube differential manometer.

The differential pressure (P_1 - P_2) relationship is written:

$$(P_1 - P_2) = \rho gh$$

where

ρ = density of column fluid.
g = acceleration caused by gravity.
h = height of column.

For most manometers, the output is transmitted visually; however, mechanically transmitted pressure signals are used (Figure 3-6-2). A variation is the high-pressure

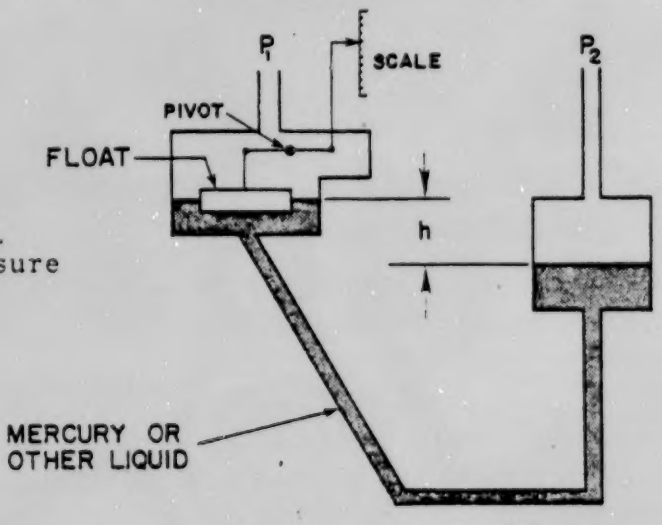

Figure 3-6-2.
Differential-pressure
manometer.

mercury manometer used in fossil-fueled power plants, which uses a magnetic linkage in conjunction with a differential diaphragm gage. This manometer is employed wherever a common interface cannot be achieved between the fluid being measured and the manometer (a diaphragm or sim-

ilar structure is interposed that, in turn transmits the pressure signal).

Elastic Elements

Metallic or mechanical pressure-sensing devices come in a variety of forms; there are slack and rigid diaphragms, multiples of stacked diaphragms, corrugated bellows and the bourdon tube. The latter comes with single, helical or spiral turns (Figure 3-6-3). A bourdon tube is described as a

Figure 3-6-3.
Bourdon tubes.

small, curved or twisted, hollow tube that deforms slightly when pressure inside it is increased or decreased. In short, it is a free-end tube that varies in position relative to applied internal pressure.

To transfer a bourdon tube's mechanical movements to a local meter, or control room console or a switch for starting a pump, a motion-balance type of mechanical system is used. This mechanism transfers the sensor motion to a pointer, recording pen or transducer mechanism (Figure 3-6-4).

A second method used to transmit sensor output is called "force-balance." This method limits free motion of the sensor by an active mechanical or electrical means (Figure 3-6-5). Its effect can reduce actual mechanical motion of the sensor

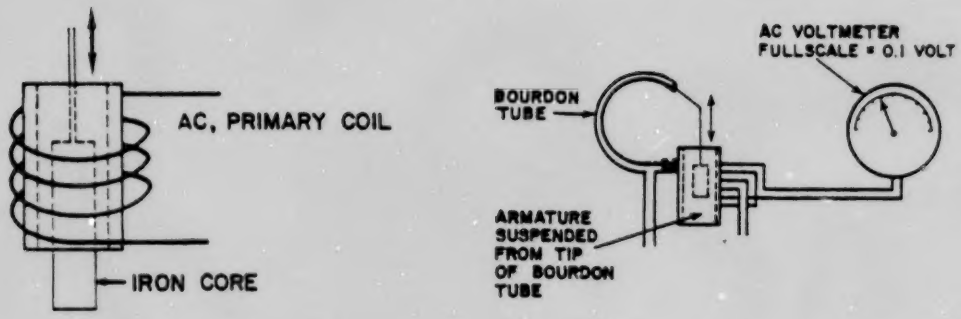

Figure. 3-6-4. Example of motion balance mechanism for pressure transmission.

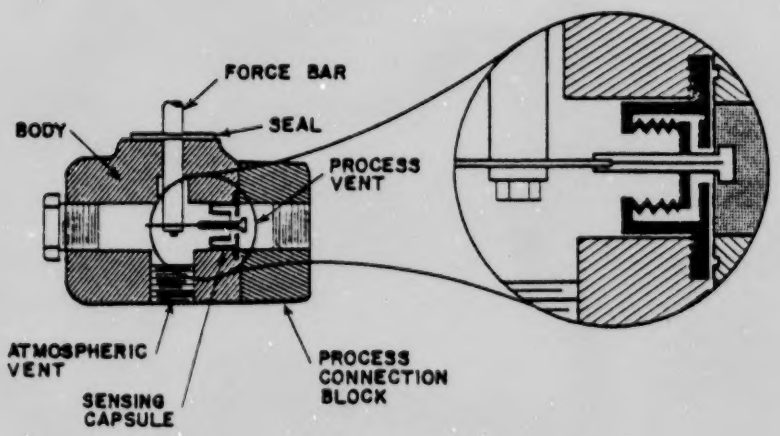

Figure 3-6-5. Force-balance pressure transmitter.

to as little as a few thousandths of an inch throughout its range of operation.

Bellows Element

A bellows element is a limited, expandable, collapsible, axially flexible enclosure. The bellows, which con-

sists of a series of specially fabricated corrugations, is generally used for relatively low-pressure and low-vacuum measurements. Bellows, like diaphragms, are commonly used with pressure-sensing systems as seals to protect sensing elements from corrosion and clogging.

Diaphragm Elements

Diaphragm-type measuring devices are normally used to determine differential pressures. The two sides of a diaphragm are isolated from each other. High pressure is applied to one side and low pressure to the other side. Any movement of the diaphragm, caused by a pressure difference across it, is transmitted through a connecting link to a transducer (Figure 3-6-6).

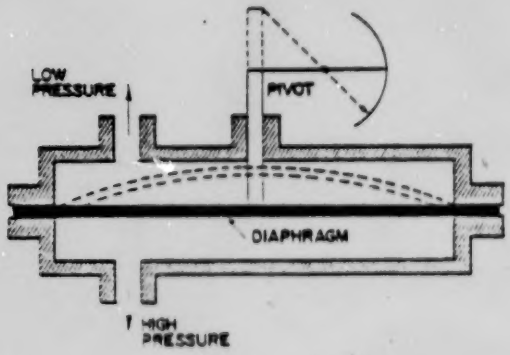

Figure 3-6-6.
Diaphragm-type measuring device with transducer.

Probe Elements

The use of probes is generally limited to fluid dynamic applications involving measurements of total flow rates, in which local variations of velocity and pressure (in a flow channel) are considerations.

Special Pressure Elements

There are occasions in power plants when unique or special pressure-measuring devices are required. These are normally associated with a laboratory or support service. Two examples of special elements are the Pirani/Thermal conductivity gage and the alphatron instrument.

The Pirani gage (Figure 3-6-7) measures pressures through a change in the thermal conductance of a gas. Heat

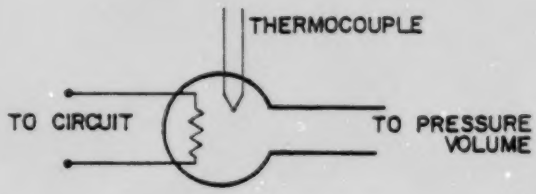

Figure 3-6-7.
Pirani pressure elements.

loss from the filament is dependent upon conductivity of the gas and upon filament temperature. The lower the pressure, the lower the thermal conductivity and the higher the filament temperature.

An alphatron is a radioactive, ionization-type gage (Figure 3-6-8) that works on the same principle as any

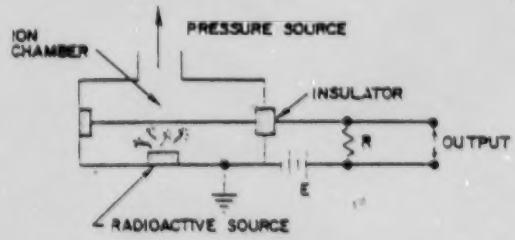

Figure 3-6-8.
Ioniation pressure gage.

other ionization chamber. An internal alpha or beta radioactive source ionizes the enclosure's gas. The degree of ionization is measured by the chamber's voltage output, or current, depending on design. The degree of ionization is a direct linear function of pressure over a wide range of pressures.

For very low pressures, the mean free ionizing particle (alpha or beta) path is so large that only a few collisions with the gas are probable in the gage enclosure.

Transducers

Pressure measurements usually center around physical displacements in tubes, bellows, diaphragms or liquid columns. A transducer converts these displacements into electrical, magnetic, pneumatic or similar output signals for control, recording or analysis functions.

Displacements by a mechanical device (generally a few millimeters or less) may be "transduced" by capacitance, electronic inductance, magnetoelectric, piezoelectric, radioactive and resistive transducers.

The force-balance assembly used extensively in power plants balances the displacement output of (for example) a bourdon tube by an equal force on a force bar. Any force-bar movement causes minute movement of some type of detector, sensor or armature (Figure 3-6-9), which changes the current flow in the detector's secondary winding. This current is usually amplified from 10 to 50 milliamperes and applied to a pressure signal receiver and a feedback coil. In the feedback coil, the current causes a force, balancing the original force-bar movement, which extends the transmitter range.

Movable-core transformer (MCT) transducers are used extensively in pressure-signal transmission. An MCT is made up

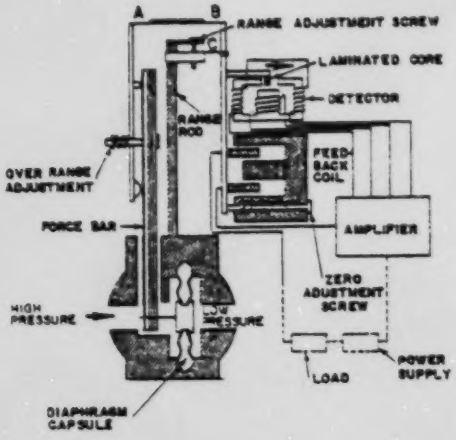

Figure 3-6-9.
Differential-pressure transmitter, electronic type.

of one primary and two secondary windings. When the core (primary winding) moves through the secondary windings (Figure 3-6-10), the output is varied because of the changes in the inductive coupling. The signal (output) normally varies between ± 10 V d.c.

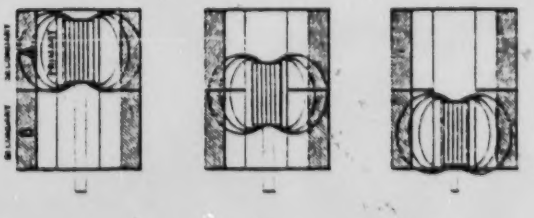

Figure 3-6-10.
Movable-core transformer (in three positions).

The last transducer to be discussed, the strain gage, measures more than just the conventional fluid pressure variable. It is used to determine the results of applied pressure as they relate to large structural members under stress, such as pressure vessels. They may measure the

yielding of containment structures to internal pressures, or the motion of snubbers. And they are used to detect torque.

Basically, a strain-gage transducer is a wire, foil or semiconductor resistor element - usually bonded to a diaphragm or other semirigid material - designed to yield linearly with pressure (strain). Deflection of a diaphragm alters the gage's resistance and unbalances an associated electrial bridge circuit.

LEVEL SYSTEMS/PRESSURE TYPE (SENSING/TRANSMISSION)

Level is position of the interface between phases. Level is treated from two viewpoints: 1) defining the position of an interface and 2) indirectly measuring volume.

Since level is defined in terms of head or pressure, the pressure-measuring devices and transducers previously described are used for level sensing and transmission, and require little additional detail. Usually, level sensors (in both PWR and BWR systems) are differential-pressure gages or a series of pressure-actuated switches. The steam systems of all nuclear- and fossil-fueled power plants include a variety of level sensors, ranging from simple sight tubes to complex pressure transducers.

The simplest technique for measuring level is a transparent sight glass connected to the vessel containing the liquid (Figure 3-6-11).

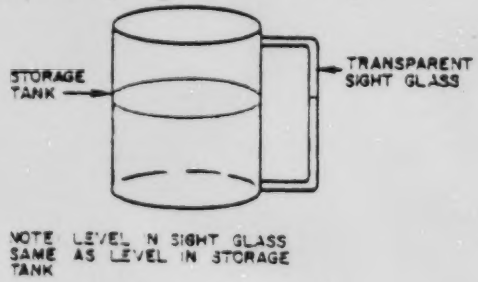

Figure 3-6-11.
Transparent sight glass for measuring levels.

The most common systems for level measurement are differential-pressure meters. In application, the minimum level tap is connected to the high-pressure side of a diaphragm or bellows chamber, while the low-pressure side is connected to the volume above the liquid (Figure 3-6-12). The differential-pressure cell, with its diaphragm, is connected to a force-balance (or similar) transducer, which transmits level value to control-room indicators, recorders, controllers and so on.

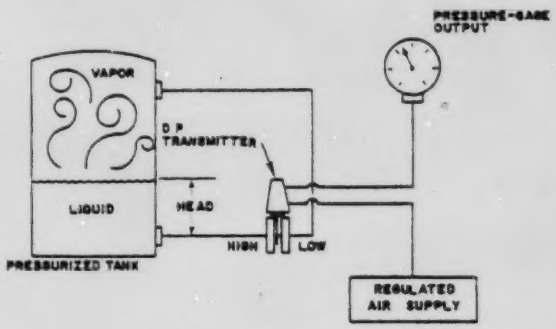

Figure 3-6-12.
Differential-pressure head-measuring device.

A very common level indicator for open vessels is the bubbling manometer. Basically, air is forced through an inverted, open-ended tube placed vertically in the vessel's fluid. Bubbles are allowed to barely emit from the open end of the tube. Connected to the air supply to the tube is a manometer or pressure gage that measures pressure required to emit the bubbles (depth of liquid above open-ended tube is the measure of pressure).

OPERATING CHARACTERISTICS

The operating characteristics of sensing devices for either level or pressure measurements in power plants are essentially the same. Even flow measurements utilize many of the above pressure-measuring devices.

Liquid-column pressure-sensing and level-sensing devices are generally limited to conventional uses in power plants.

SPECIFIC APPLICATIONS

Manometers measure pressures or pressure differentials with sufficient accuracy to be acceptable for "ASME Performance Test Code" purposes.

Bourdon tube gages are used for certain test procedures (such as hydrostatic testing of pressure parts and boiler efficiency tests) in which a higher degree of precision is required. Note: Dead-weight gages are preferred over bourdon gages when the thermal properties of steam and water must be known accurately.

Diaphragm-type gages are suitable for reading fluid pressure drops through boillers: they can be used to measure differentials from 2 to 1000 psi at pressures up to 6000 psi.

Bellows, which enjoy a wide latitude of applications, are particularly prevalent in the control of processes; for example, they are used for automatically controlling pumps, based on level requirements, pressure requirements or flow requirements.

CALIBRATIONS

Pressure is one of the easiest process variables to tie back to the fundamental standards of force and length. Precision manometers, standard test gages and dead-weight testers are commonly used for pressure instrument calibration. A dead-weight tester (Figure 3-6-13) measures pressure in terms of force and area (pressure = $\frac{\text{force}}{\text{area}}$). Pressure up to 100,000 psi can be measured by this device with

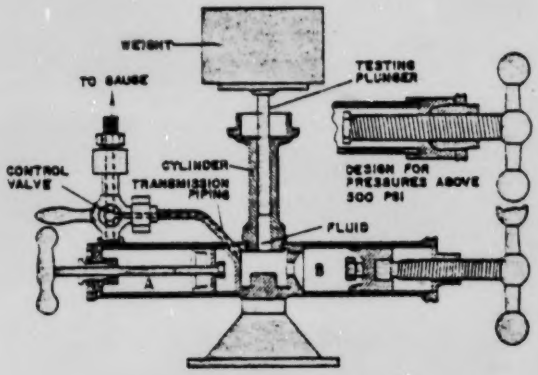

Figure 3-6-13. Dead-weight tester.

an accuracy of 0.01%.

In this type of testing device, the gage is subjected to hydrostatic pressure, created by applying weights to a plunger. The weighted plunger applies pressure to the fluid (usually an approved type oil) in the cylinder, which is transmitted to the gage through the transmission piping and the control valve. The plunger itself exerts a pressure of 5 or 10 psi, and additional weights in appropriate sizes are provided. Normally, weights that exert pressures equal to 5, 10, 20 and 100 psi are available. The gage

reading is compared with the pressure of the calibrated weights.

The accuracies of dead-weight testers are limited by two factors:

Friction between cylinder and piston.

Uncertainty in piston area. (This area is not the area of the piston itself but an "effective" area dependent upon clearance and spacing and viscosity of oil.)

With accuracy referenced to a standard at the National Bureau of Standards, this device can be used to calibrate all types of pressure-indicating or controlling instruments (gages, switches, transmitters, transducers and differential-pressure units).

EXERCISES

1. An air bubbler is used to measure liquid level. If a pressure of 10 psi is obtained and the liquid is water, what is the level down to the bubbler exit?
2. Draw the basic features of 1) a bourdon tube, 2) a diaphragm and 3) a bellows gage.
3. Identify at least one power plant application of each of the three gages mentioned above.
4. Define the term, "transducer" and list three types.
5. Suggest types of sensors and transducers used to mea-

sure 1) levels in a water storage tank, 2) ventilation-filter pressure drops, 3) differential pressures across orifices and 4) reactor vessel pressures.

6. Given: Differential pressure across an orifice (measured by a water manometer) of 4.5 inches of water at 20°C; pipe I.D. of 10.0 inches; total system head pressure of 40.0 psi. Find: Volumetric flow in pipe. Hint: Review Module 3-5, "Basic Principles of Flow Measurement."

MATERIALS

1 dead-weight tester (12 to 500 psi range).
1 bourdon tube (10 to 500 psi range).
1 mercury barometer.
1 instrument-air gage (5 to 40 inches Hg).
1 length of suitable tubing.
Dead-weight tester fluid (sufficient for experiment).
1 30-inch mercury U-tube manometer.

INSTRUMENT-AIR GAGE CALIBRATION

1. Determine atmospheric pressure (use mercury barometer); record on Data Table 3-6-1.
2. Assemble manometer as shown in Figure 3-6-14.

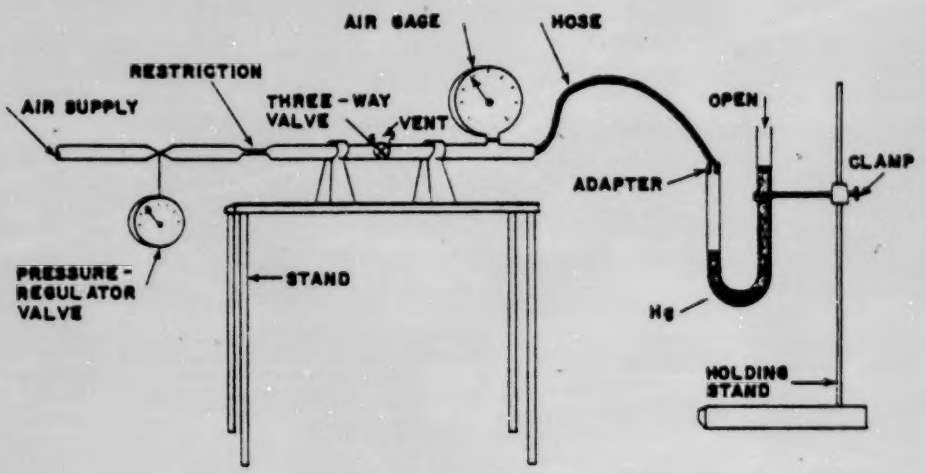

Figure 3-6-14. Air-gage apparatus.

3. Use 30-inch mercury manometer; calibrate instrument-air gage at approximately 10, 15, 20 and 25 inches of mercury; record on Data Table 3-6-1.
4. Plot data on linear graph paper. (Assume that manometer readings are exact.)
5. Explain results of plot.

BOURDON-TUBE GAGE CALIBRATION

1. Assemble dead-weight tester as shown in Figure 3-6-15.

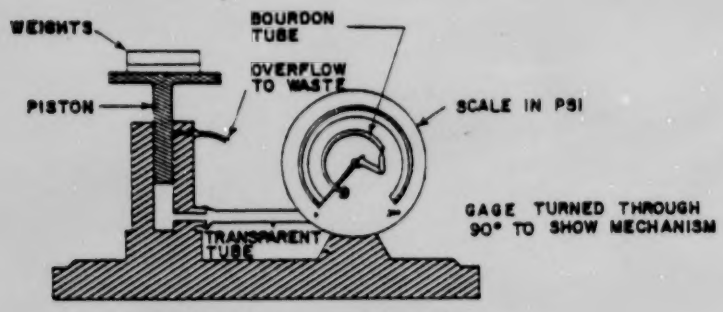

Figure 3-6-15. Arrangement for calibration of pressure gage.

2. Remove piston and fill cylinder with water (to overflow). Clean trapped air from transparent tube. (A small amount of air in system will not affect experiment.) Place piston in cylinder; allow it to settle.
3. Add weights in convenient increments; at each increment, read pressure gage; remove weights incrementally and read gage; record results on Data Table 3-6-2.
4. From Data Table 3-6-2, plot (on linear scales) the increasing and decreasing gage reading as a function of true pressure; also, plot (separately) gage error as a function of pressure. Hysteresis, friction and backlash should be reflected by differences, if any, in increasing and decreasing pressure readings on the first plot; any scale gradation error should be reflected in the second plot.
5. Measure cross-sectional area of piston; weigh piston; record area and weight on Data Table 3-6-2.

6. Suggest ways of improving test apparatus. Are readings in psi, psia or psig?

DATA TABLE

DATA TABLE 3-6-1

INSTRUMENT-AIR GAGE CALIBRATION

Barometric Pressure: _____ in Hg.

Temperatures: Initial _____ °F; Final _____ °F.

Actual Air Gage Reading (in. Hg)	Manometer Height Reading (in. Hg)	% Error

Average % Error: _____.

Model/Type of Air Gage: _____.

DATA TABLE 3-6-2
BOURDON TUBE CALIBRATION

Weight Added to (pounds)	Total Load on Piston (pounds)	True Pressure (psi)	Gage Reading (psi)		% Error
			Increasing Pressure	Decreasing Pressure	
				X	
				X	
				X	
				X	
				X	
				X	
			X		
			X		
			X		
			X		
			X		
			X		

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TEST

Read each question carefully. Be sure your responses give the specific information each question requires. Your answers should be brief. Use the backs of the test if you need more space.

1. Describe the principle of operation of the strain gage.

2. Name two areas or parts of a power plant where it is necessary to make differential-pressure measurements of fluid flow.

   a.

   b.

3. What is one principal application of an inclined-tube differential manometer?

4. What type of manometer is usually used in fossil fuel plants wherever a common interface between the fluid being measured and the manometer is not possible?

5. What is an elastic chamber? What are two types of elastic chambers?

6. Briefly describe how a diaphragm-type device determines differential pressure.

7. Describe how <u>either</u> the Pirani gage or the alphatron measure pressure.

8. What is the purpose of a transducer in pressure measurement? What are three means by which the displacements by a mechanical device can be "transduced"?

9. Describe how the movable-core transformer (MCT) transducer works.

_____

_____

_____

_____

10. Name two techniques (devices) for measuring level.

a. _____

b. _____

11. Name one principal application for bellows and for Bourdon tube gages.

a. Bellows: _____

b. Bourdon tube: _____

12. Briefly describe calibration of pressure instruments by the dead weight method.

_____

_____

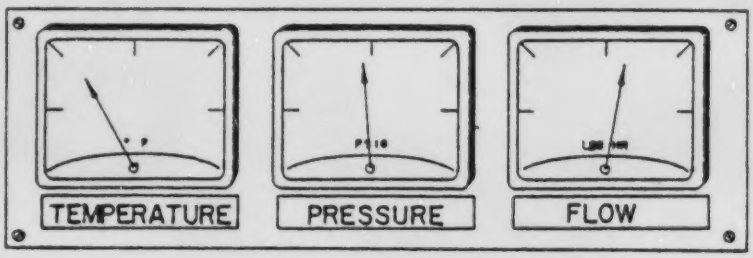
_____

_____

_____

NUCLEAR TECHNOLOGY

MODULE 3-7 FLOW-SENSING DEVICES: DIFFERENTIAL-PRESSURE FLOWMETERS.



PRINCIPLES OF
PROCESS INSTRUMENTATION

COURSE 3

COURSE MODULES

COURSE 3 PRINCIPLES OF PROCESS INSTRUMENTATION

MODULE 3-1	Temperature-Sensing Devices: Glass-Bulb Thermometers
MODULE 3-2	Temperature-Sensing Devices: Thermocouples
MODULE 3-3	Temperature-Sensing Devices: Resistance Thermometers
MODULE 3-4	Temperature-Sensing Devices: Pyrometers
MODULE 3-5	Basic Principles of Flow Measurement
MODULE 3-6	Pressure-Sensing Devices
MODULE 3-7	Flow-Sensing Devices: Differential-Pressure Flowmeters
MODULE 3-8	Flow-Sensing Devices: Linear Flowmeters

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INTRODUCTION

The many devices for measuring fluid flow include flow nozzles (flow tubes) and venturi tubes. Pressure drops (differentials) created by these restriction-type devices can be converted by calculations into flow rates.

This module defines basic terms used in differential-pressure flow measurements, explains basic operating principles of various primary flow-detecting elements and discusses more prominent secondary elements (transducers). Also, specific characteristics, applications, advantages and disadvantages, installations and maintenance of these devices are examined. And tests, calibrations and uses of standards are discussed in terms of plant applications.

MODULE PREREQUISITES

The student should have completed Module 3-6, "Pressure-Sensing Devices," and its prerequisites.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms, using assigned units, where applicable:
   - Discharge coefficient.
   - Diameter ratio.
   - Reynolds number.
   - Taps.
   - Throat area.
   - Streamliners.
2. List and explain operating principles (include descriptions, characteristics and applications) of various differential pressure sensing flowmeters.
3. Discuss flow-measurement secondary elements (transducers).
4. Sketch a typical differential-pressure flow-sensing device and transmission channel.
5. Install an orifice plate and a venturi tube in pipes; measure pressure drops as functions of flow; calculate flows, based on nominal discharge coefficients, for each device.
6. Calibrate an orifice plate and a venturi tube by making a differential-pressure versus flow curve; calculate discharge coefficient.

FLOWMETER FUNDAMENTALS

If a constriction is placed in a pipe in which a fluid is flowing, there will be an increase in the fluid velocity, and an increase in kinetic energy at the constriction point. This statement, based on the "conservation of mass" relationship (Figure 3-7-1), can be calculated as follows:

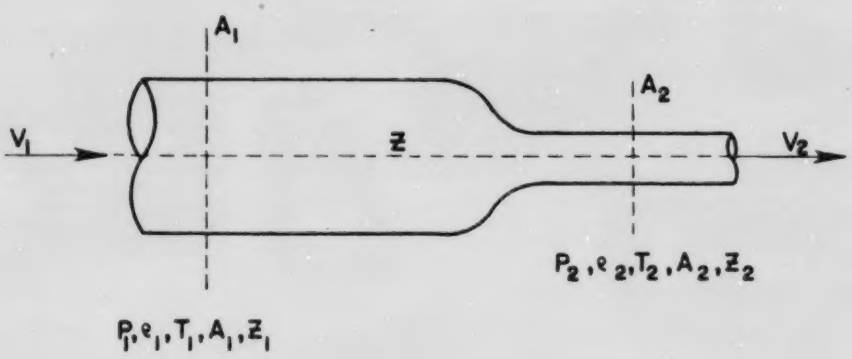


Figure 3-7-1. One-dimensional flow system.

$$Q = A_1 V_1 \rho_1 = A_2 V_2 \rho_2$$

Equation 3-7-1
(Equation = Eq.)

where

Q = volumetric flow (a constant).

A = area of pipe (cross sectional).

ρ = density of fluid.
V = velocity of fluid.
T = temperature of fluid.

Velocities are considered to be average velocities; in reality, however, velocity varies across the pipe diameter, beginning as zero at the wall to a maximum in the center. In an ideal case, the Bernoulli equation can be combined with Equation 3-7-1:

$$Q = CA\sqrt{2gh} = A_2 V_2 \qquad \text{Eq. 3-7-2.}$$

where

C = coefficient of discharge for constriction.
A = cross-sectional area of constriction.
g = gravitational constant = 32.2 ft/sec^2.
h = differential pressure (static) or head, $(P_1 - P_2)$.

This relationship is called the "square-root" law and, basically, applies to any type of restriction. It is confined, however, to incompressible ideal fluids in this module.

The coefficient of discharge is an empirical constant, based on type of constriction (diameter ratio), and is equivalent to:

$$C = \frac{Q_{actual}}{Q_{ideal}}. \qquad \text{Eq. 3-7-3}$$

This constant also depends on the magnitude of the Reynolds number (N_{Re}), a function of turbulence, density, viscosity and velocity of the fluid. Thus, the constant, C, actually includes a separate constant called the "approach factor:"

$$\frac{1}{\sqrt{1 - (d/D)^4}} \qquad \text{Eq. 3-7-4}$$

where

d = area, A_2, of constriction (such as an orifice).
D = diameter or area, A, of pipe.

(Note: In the actual development of working equations for commercial applications of head or differential-pressure flowmeters, Equations 3-7-2 and 3-7-4 require additional correction factors for specific fluids, temperature, and other variables. These factors are normally found on the specification sheets for such devices.)

In short, C is introduced to account for deviations from the ideal Bernoulli equation. Its value is generally near unity, although precise determination must be achieved by empirical calibration.

Pressure-sensing connections, or taps, are small holes located accurately (in accordance with recognized standards)

so that published discharge coefficients for a specific flowmeter are applicable. (The differential pressure that measures static pressure varies with choice of taps.)

In power plants, pitot tubes occupy a place of only minor importance as primary elements for head flowmeters. They are, however, effective tools for spot checks and scans of flow streams. The latter is important in determining velocity distributions or profiles across pipes or ducts.

DIFFERENTIAL-PRESSURE DEVICES AND CHARACTERISTICS

Orifices, nozzles and venturis (Figure 3-7-2) are by

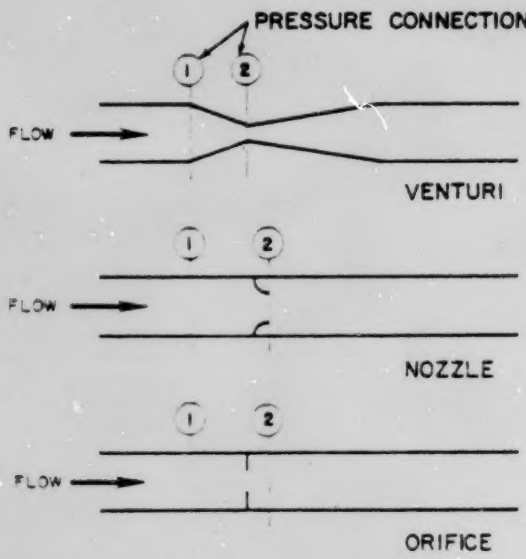


Figure 3-7-2. Three typical obstruction meters.

far the most common classifications of flowmeters for use in power plant closed circuits.

ORIFICE PLATES

The orifice plate is probably the earliest and most common primary device in commercial use. Characteristics favoring its choice include:

Ease of manufacture.
Reproducibility.
Ease of inspection.
Ease of installation.
Economy.

The orifice plate is simply a thin disk clamped between gaskets in a flanged joint. Usually, a concentric circular hole in the plate is smaller than the internal pipe diameter.

Pressure connections for attaching a differential gage (or separate static gages) are made at side holes in the pipe wall on both sides of the plate. The plate hole may be square, knife edged or beveled edged (Figure 3-7-3).

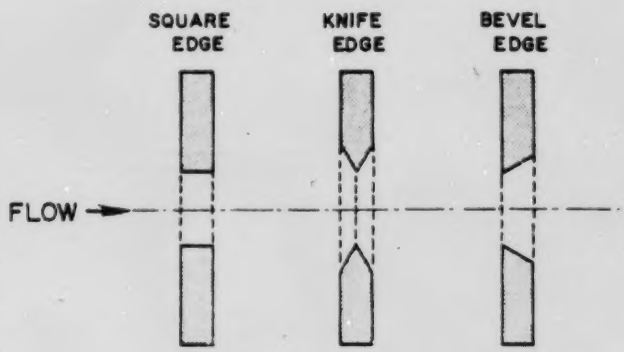


Figure 3-7-3.
Orifice plates.

ASME-designed orifice plates can be used without individual calibration with great assurance of accuracy.

In a typical orifice meter (Figure 3-7-4), tap locations must be located very accurately according to one of three arrangements recognized by the ASME Code.

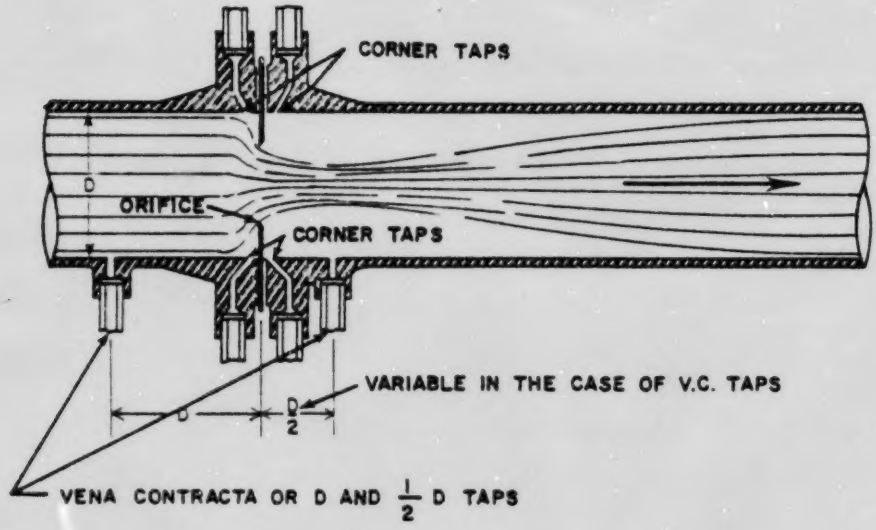


Figure 3-7-4. Typical orifice meter.

Flow through a sharp-edged or square concentric orifice plate is characterized by a change in velocity, which reaches a maximum at a point slightly downstream from the orifice. Beyond that point, velocity reduces to its original value.

(Eccentric plates - off-center orifices - are used infrequently in power plants; they are more apt to be used in slurries and "dirty" fluids.)

The basic working equation for an orifice plate (based on Equation 3-7-2) may be stated as follows:

$$Q = C_o A \sqrt{\frac{2g(P_1 - P_2)}{\rho[1 - (\frac{D_o}{D_1})^4]}}$$

Eq. 3-7-5

where

$Q = \bar{V}_o A$.

= Volume flow rate.

$\bar{V}$ = average fluid velocity through orifice, ft/sec.

A = cross-sectional area of orifice.

D_o = diameter of orifice, ft.

D_1 = inside diameter of pipe, ft.

C_o = orifice discharge coefficient, which varies with type of orifice, position of tap and Reynolds number (N_{Re}).

P_1 = upstream pressure.

P_2 = downstream pressure.

ρ = weight density of fluid, lbf/ft^3.

$\frac{D_o}{D_1}$ = β, diameter ratio.

The above variables may be related to C (Figure 3-7-5). Given a known volumetric flow rate, orifice and pipe dimensions, fluid density and expected N_{Re}, a discharge coefficient can be determined. In turn, expected differen-

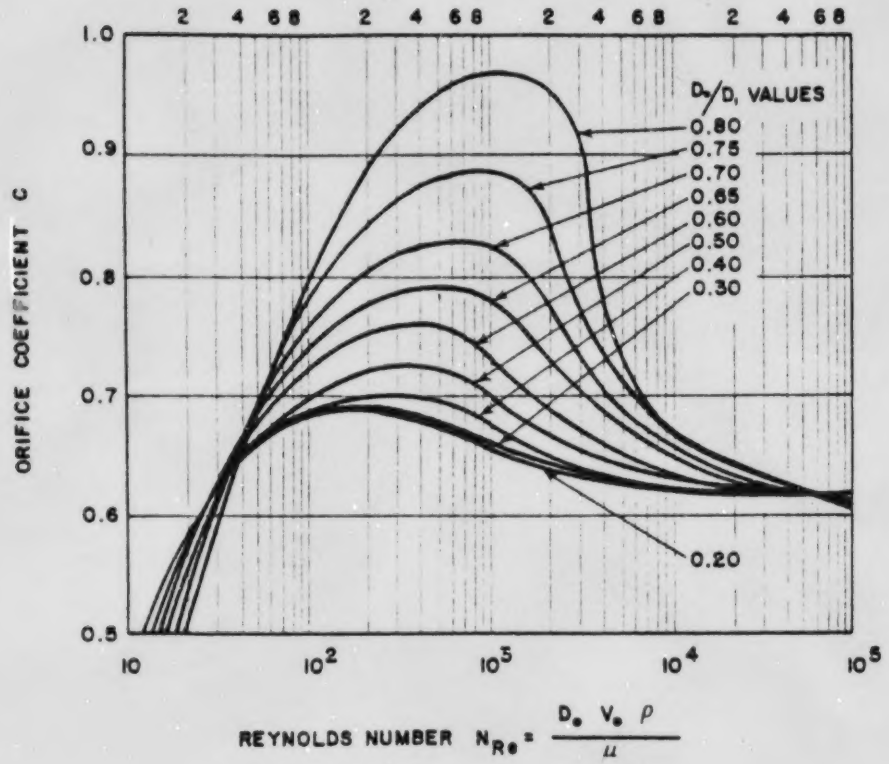


Figure 3-7-5. Orifice coefficient C for circular square-edged orifice with corner taps.

tial pressure also may be calculated. In actual cases, the calibrated values of an orifice are known and, in turn, an unknown flow differential pressure can be measured. This pressure is plotted versus flow (Figure 3-7-6).

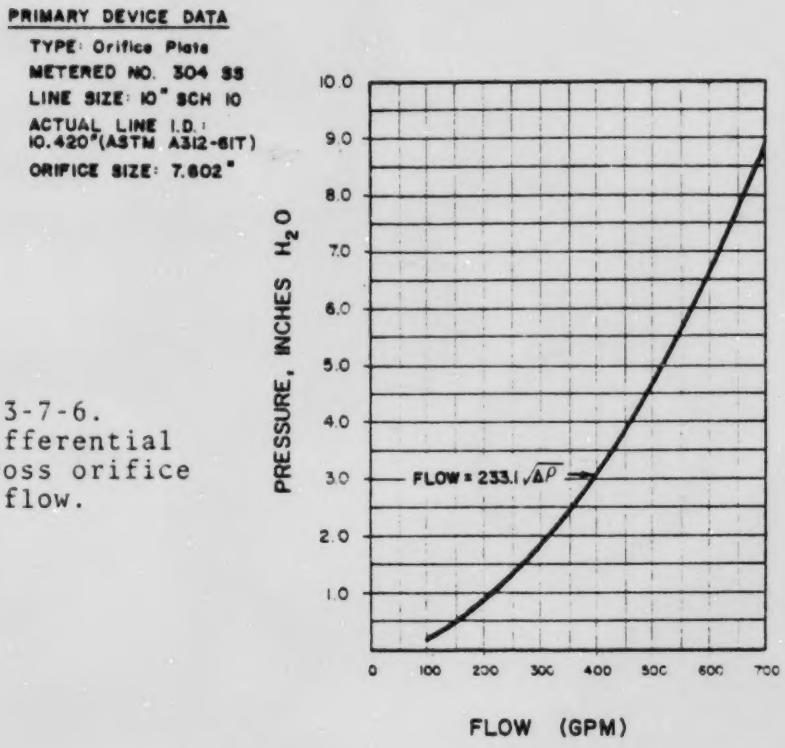


Figure 3-7-6.
Manometer differential pressure across orifice versus flow.

EXAMPLE

Given: Pipe I.D. = 4 in = D_1.

Orifice I.D. = 2 in = D_o (square-edged with corner taps).

Reynolds number = 4000.

Fluid = water.

Find: Orifice coefficient and flow as a function of differential pressure.

Solution: For a Reynolds number of 4000 and

D_o/D_1 of 0.5, orifice coefficient (C_o) is given as 0.66 from Figure 3-7-5; therefore:

$$C_o = 0.66.$$

By using Equation 3-7-5:

$$Q = C_o A \sqrt{\frac{2g\ (P_1 - P_2)}{\rho\ [1 - (\frac{D_o}{D_1})^4]}}$$

$$= (0.66)(\frac{\pi\ 1^2}{12^2}\ ft^2)$$

$$x \sqrt{\frac{2 \times 32.2\ ft/sec^2 \times (P_1 - P_2)}{62.4\ \frac{lbf}{ft^3}\ (1 - [\frac{2/12}{4/12}]^4)}}$$

$$= (0.66)(0.0218)$$

$$x \sqrt{\frac{64.4\ \frac{ft}{sec^2} \times (P_1 - P_2)}{62.4\ lbf/ft^3 \times (0.9375)}}$$

$$= 0.0144 \text{ ft}^2 \sqrt{1.101 \frac{\text{ft}^4}{\text{sec}^2 \times \text{lbf}} (P_1 - P_2)}$$

$$= 0.015 \sqrt{P_1 - P_2}, \frac{\text{ft}^3}{\text{sec}}$$

where P_1 and P_2 are pressure in psf.

If P_1 and P_2 are given in psi,

$$Q = 0.181 \sqrt{P_1 - P_2}, \text{ ft}^3/\text{sec}.$$

FLOW NOZZLES

Smaller holes in an orifice plate cause flow to be pressed together further downstream of the orifice; thus the discharge coefficient departs measurably from unity. In contrast, a flow nozzle gives a smooth, convergent section, which discharges the flow more parallel to the axis of flow and with less convergence and pressure loss (Figure 3-7-7).

Briefly, the nozzle is described as a short cylinder, one end of which is flared to form a flange that can be clamped between pipe flanges. The purpose of the smooth, curved entrance to the nozzle is to lead the fluid smoothly (with minimum turbulence) into the measuring section (throat area).

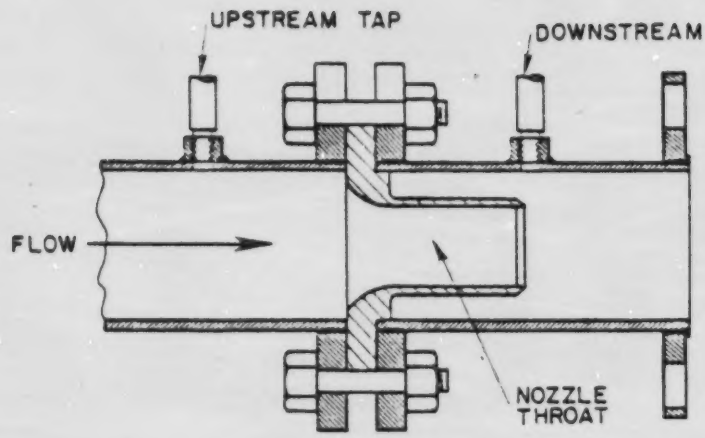


Figure 3-7-7. Flow nozzle with pipeline taps.

The flow nozzle passes approximately 60 percent more flow than an orifice with the same differential pressure and the same ratio of throat-diameter to internal-pipe-diameter.

A flow nozzle can be installed in a welded pipe, but it cannot be used to meter flow in either direction. It is successfully used in installations where limited lengths of straight pipe limit orifice usefulness. Turbine engineers use flow nozzles extensively in turbine performance testing.

VENTURI TUBES

The venturi tube is essentially a smooth extension of the flow nozzle with a subsequent gradual, divergent, conical section that expands until the original pipe diameter is again attained (Figure 3-7-8). This tube, used mostly in large pipes, is more accurate than an orifice plate or flow nozzle, but considerably more expensive and more difficult to install.

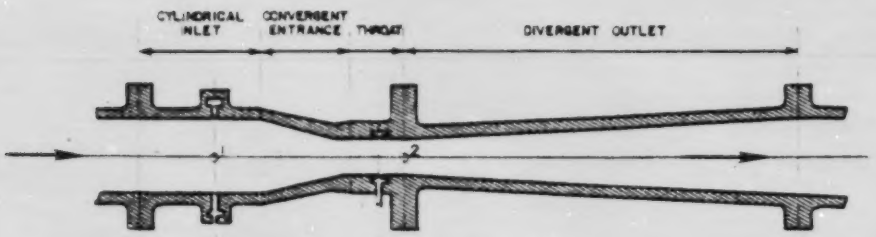


Figure 3-7-8. Typical venturi tube.

The basic working equation for a venturi tube is similar to that used for orifice calculations:

$$Q = C_v A_2 \sqrt{\frac{2g\ (P_1 - P_2)}{\rho\ [1 - (\frac{A_2}{A_1})^2]}}$$

Eq. 3-7-6

where

$Q = \bar{V}_2 A_2$.

$\bar{V}_2$ = average velocity at point 2, ft/sec.

$P_1 - P_2$ = differential pressure, lbf/ft^2.

A_2 = cross-sectional area at point 2, ft^2.

ρ = weight density of fluid, lbf/ft^3.

C_v = venturi discharge coefficient, which varies with geometry, flow rate and fluid.

Venturi tube design favors their use in continuous-flow slurries and suspended matter that normally might clog or alter the characteristics of an orifice plate or its taps.

PITOT TUBES

Pitot tubes were briefly discussed in earlier modules. They normally occupy a minor role in the measurement of liquid flows in power plants but do have considerable importance in gaseous flow measurements.

In general, a pitot tube for determining flow by differential pressure, consists of two members, one for indicating the sum of the static and velocity pressures at a point in a body of fluid in motion, and the other for indicating static pressure only. The first is known as an "impact tube" and the pressure registered by it as the "total head" or "stagnation pressure" (Figure 3-7-9).

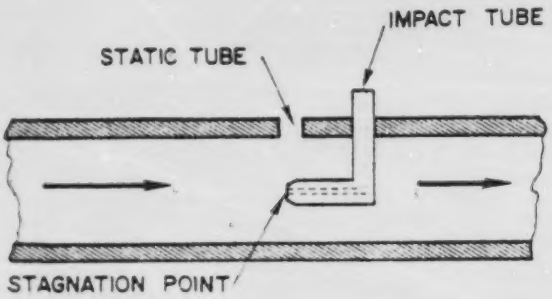


Figure 3-7-9.
Pitot tube, independent static-tap.

Beginning again with the Bernoulli equation, it can be shown that flow past the pitot tube is characterized by the same general type equations previously discussed for orifice plates and venturi tubes:

$$V_1 = C_p \sqrt{\frac{2g\ (P_1 - P_2)}{\rho}}$$

where

V_1 = velocity of fluid in line with pitot head.

C_p = impact coefficient.

P_1 = impact pressure (absolute) (if $V_2 = 0$).

P_2 = static pressure in flowing fluid, absolute.

ρ = weight density, lbf/ft^3.

It is important to note that velocity is measured at only one point in a cross section of fluid flow (contrasted with other flow elements, which consider the average or effective velocity of an entire stream).

ELBOW DEVICES

There are many instances in which it is only necessary to know that a loss or a relative drop in flow has occurred. For example, in a PWR, the primary coolant flow rate in each loop is established by a constant-speed pump. To detect a loss or reduction in flow, an elbow differential-pressure device (Figure 3-7-10) is used. $P_1 - P_2$ is an established value for the desired flow. As the primary coolant flow drops off, the differential pressure is reduced. This signal annunciates and, in some cases, trips the reactor.

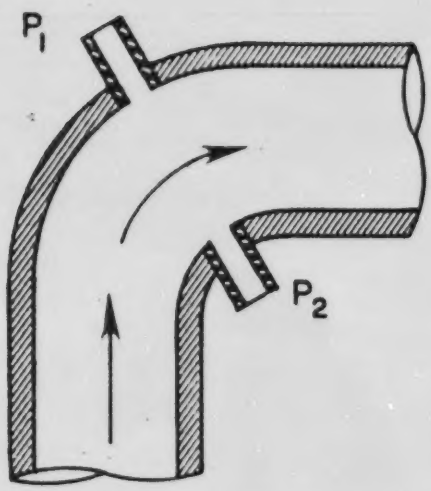


Figure 3-7-10.
Elbow differential-pressure flow sensor.

INSTALLATION/OPERATION

Regardless of the primary element selected, certain important installation factors should be considered to ensure accurate measurements:

Location in piping, in relation to a) bends (elbows) b) changes in pipe cross section.

Possible need for approach-straightening vanes (streamliners).

Location and type of pressure taps.

Dimensions and conditions of pipe surface before and after element.

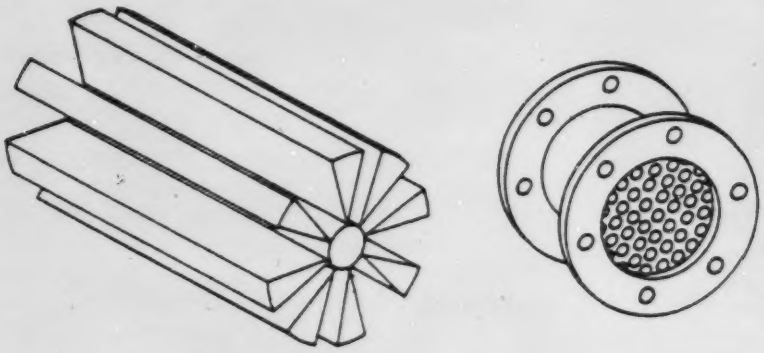
Position of element relative to direction of fluid flow.

Type and arrangement of piping from primary element to differential-pressure measuring instrument.

Abnormal velocity distribution at pressure measurement points influences readings from any of the head flowmeters previously discussed. For this reason, it is important to

install elements with adequate lengths of straight, smooth approach pipe.

When the piping layout, especially adjacent elbows and partially closed valves, do not allow sufficient streamlining of the flow to eliminate pressure disturbances, straightening vanes are used. These vanes eliminate swirls, cross-currents and eddies set up by fittings, valves and elbows upstream (Figure 3-7-11). These units are welded into pipe



One piece Tube, end view

Figure 3-7-11. Straightening vanes.

nipples and mounted between companion flanges to form line sections.

TRANSDUCERS AND TRANSMITTERS

In remote transmission systems, a secondary element (transducer) is considered to include both the transmitter containing the measuring mechanism and the receiver. In

effect, the direct mechanical connection of a self-contained secondary element is replaced by a pneumatic or electric position-transmitting mechanism.

The two general classes of measuring mechanisms of differential-pressure transmitters (discussed in Module 3-6, "Pressure-Sensing Devices,") are the motion-balance type and the widely used force-balance type.

In a force-balance system, output is supplied to a pneumatic bellows or electromagnet that opposes the force exerted by the measuring mechanism. In a typical device, sometimes referred to as a D.P. (differential-pressure) cell or a delta-P cell (Figure 3-7-12), a change in differential pressure changes

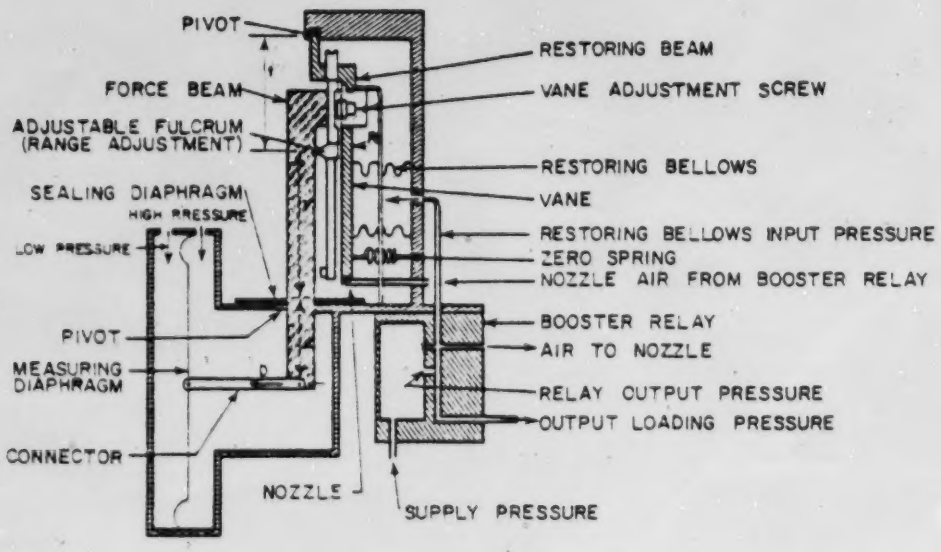


Figure 3-7-12. D.P. cell.

the air gap at a nozzle tip, thereby changing nozzle pressure. This change, in turn, is amplified to provide an output signal.

The need to determine integrated flow of a fluid (volume) in a power plant is ever present. To obtain this information, an integrator (counter) is usually driven by a constant-speed motor through a friction clutch and cam-operated mechanism such that the counter rotates during a portion of cam rotation, the duration of which is proportional to rate of flow. The amount registered during any time period is the total flow in that period.

SPECIFIC APPLICATIONS

Flow in power plants is one of the most numerous of all measured process variables. A listing of typical applications includes:

Steam flow to turbine, through restrictors.
Primary coolant flow.
Boron shim dilutions and boration.
Feedwater flow to steam generators.
Liquid radioactive waste releases.
Ventilation air flow.
Safety injection flows.
Makeup flow to tanks, systems and accumulators.
Demineralizer treatments (injections).
Letdown of primary system (used as a pressure reducer rather than flow measurement).
Instrument air flow.

Pressurizer spray diesel-fuel flow.

Isokinetic probes.

There are, perhaps, dozens of other applications. (In fossil plants, combustion air or flue gases, hydrogen flow and coolant to turbine blades and generator, fuel flow, and blowdown are typical flow applications.)

In almost every application, the flow signal is used to regulate the flow itself, to cause other flows to be regulated (steamflow-feedwater match) and to initiate protective actions, such as reactor trip in case of loss of primary coolant flow.

The elbow differential-pressure device is used in primary coolant lines to indicate relative flow rates. Restrictors (nozzles, orifices or venturis) are used in the majority of principal flow measurements noted above.

The final choice of primary and secondary elements lies in the optimum combination of advantages and disadvantages, and in the application of these devices. Table 3-7-1 lists advantages and disadvantages of the most common primary elements (as listed by the ASME Test Code 19.5;4-1959).

CALIBRATION

Commercial differential-pressure flowmeters, generally, are designed according to ASME standards. Vendors calibrate their orifices, nozzles and venturi tubes within their own very sophisticated facilities. On the basis of these calibrations, head-type flowmeters are sold with accompanying

TABLE 3-7-1

ADVANTAGES AND DISADVANTAGES OF THREE PRINCIPAL PRIMARY ELEMENT TYPES

Advantages	Disadvantages
ORIFICE	
1. Lowest Cost 2. Easily installed and/or replaced 3. High predictability of coefficient of discharge 4. Will not wear in service 5. Sharp edge will not foul up with scale or dirt 6. Adjustable type capable of wide range metering	1. Unrecoverable head loss sometimes objectionable 2. Suspended matter may build up on inlet side 3. Maximum capacity may be limited 4. Preferably limited to factors below 1,000 psi and 800F 5. Must be mounted between flanges 6. Installation of orifice and pressure connections must be carefully made
FLOW NOZZLE	
1. Handles 60% greater capacity than orifice 2. Can be welded into pipe line 3. Costs less than Venturi tube but handles same capacities 4. Used when piping layout not suitable for orifice	1. Costs more than orifice 2. Same unrecoverable head loss as orifice 3. Throat may foul up with pipe scale or dirt 4. Pressure connections must be carefully made
VENTURI TUBE	
1. Lowest unrecoverable head loss 2. Pressure connections are integral part of element 3. Requires only short length of straight pipe on inlet side 4. Best suited for measuring solids in suspension 5. Can be welded into line	1. Highest original cost 2. Highest installation costs 3. Not recommended for steam 4. Greatest weight and largest size for given line size

specification sheets (Figure 3-7-13).

By applying good engineering and installation practices, the flowmeter is then calibrated in place, by using the design data and the specification sheet.

Laboratory calibrations of flowmeters are accomplished through the use of time-related, volumetric accountability

Name TYPE 15A PNEUMATIC FLOW TRANSMITTER

Identification Tag: Water Flow

Type d/p Cell Diff. Range 0-17.93"H_2O Dry Cal.(_____ Wet)

Static Range _____ Chart No. _____ Range _____

Integrator _____ Flow Pen Reading X _____

Press. Pen Reading X _____ Integrator Reading X _____

Integrator Registers _____

FLOW DATA

Fluid Water Viscosity .54 cps. @ _____ Flow Temp. 125°F

Sp.Grav. 1.00 Base Temp. 60°F Flow Grav. .988

Press. Base _____ Flow Press. _____

Seal None Sp. Grav. _____ Barometer _____ Steam Quality _____

PRIMARY DEVICE DATA

Type Orifice Plate Material 304 SS Line Size 10"Sch.30

Flange Rating 300# R.F. Actual Line I.D. 10.136"

Straightening Vane Location _____ Pipe Diam. Upstream Vent Hole _____ Drain Hole _____

Press. Tap Location 1" Up. 1" Downstream Orifice

Size 7.602" Differential Computed for 1,000 Gals. Per min. as 17.93 nH_2O Diff. Dry Cal. _____

d = 7.602 d/D $\frac{7.602}{10.136}$ = .7500 S = .4222 Fc = .966

$$\text{Diff.} = \left[\frac{(Qm\ Gl)}{(N\ S\ D^2\ Fa\ Fm\ Gf\ Fc)}\right]^2 \quad \begin{matrix} & & & & & & \\ & 154 & 173 & 155 & 156 & 157 & 158 \end{matrix}$$

$$\text{Diff.} = \left[\frac{(1000 \times 1.00)}{(5.667 \times .4222 \times 102.7 \times 1.001 \times 1.000 \times .994 \times .966)}\right]$$

$$\text{Diff.} = (4.234)^2 = 17.93"H_2O$$

Diff. Range at 700 GPM = 8.79"H_2O
Permanent Press. loss 46%, or .46 x 8.79 = 4.04"H_2O

Figure 3-7-13. Typical orifice specification sheet.

of the fluid (direct method). Precision manometers are used to measure differential pressure in conjunction with secondary element output.

EXERCISES

1. $Q = CA\sqrt{2gh}$ is given as the basic expression for a change in pressure head measured by a head-type flowmeter.

   Why is this called a square-root relationship?
   If flow rate is doubled and all other variables remain constant, how is pressure head changed?
   Identify each function in the above equation.

2. Describe and sketch three principal types of differential-pressure flowmeters; give advantages and disadvantages of each.

3. Sketch and discuss a typical differential-pressure transducer of the force-balance type.

4. Given: 10-inch I.D. stainless steel pipe; average flow of 10 ft/sec of 500°F water; orifice plate $D_o/D_1 = 0.8$.
   Find: Volumetric and mass flow rates.

5. Given: 8-inch (nominal schedule 40) pipe; 70°F water flow.
   Find: Differential pressure versus flow (similar to Figure 3-7-6) for the following:
   Square orifice.
   Venturi tube.
   Flow nozzle.

6. Use ASME Test Code; find location for installing pressure taps in 2.0-inch I.D. pipe for a) an orifice, b) a venturi tube and c) a flow nozzle.

MATERIALS

1 series coupling (orifice plate and venturi tube) in horizontal length with associated scaled (water) manometers and connections at proper tap location. (A commercial classroom apparatus is recommended.)

1 water supply, with variable flow valve and assured constant flow rate.

1 calibrated collection (weighing) tank.

Specification sheet on orifice plate and venturi tube to be used.

Adequate length of straight pipe, upstream from each meter.

1 stopwatch.

PROCEDURES

MEASURE PRESSURE DROPS AND CALCULATE FLOWS

If available, this procedure should be performed with a commercial classroom flowmetering device.

1. Assemble orifice plate, venturi tube, piping and manometers as shown in Figure 3-7-14. Be sure to follow vendor's instructions.

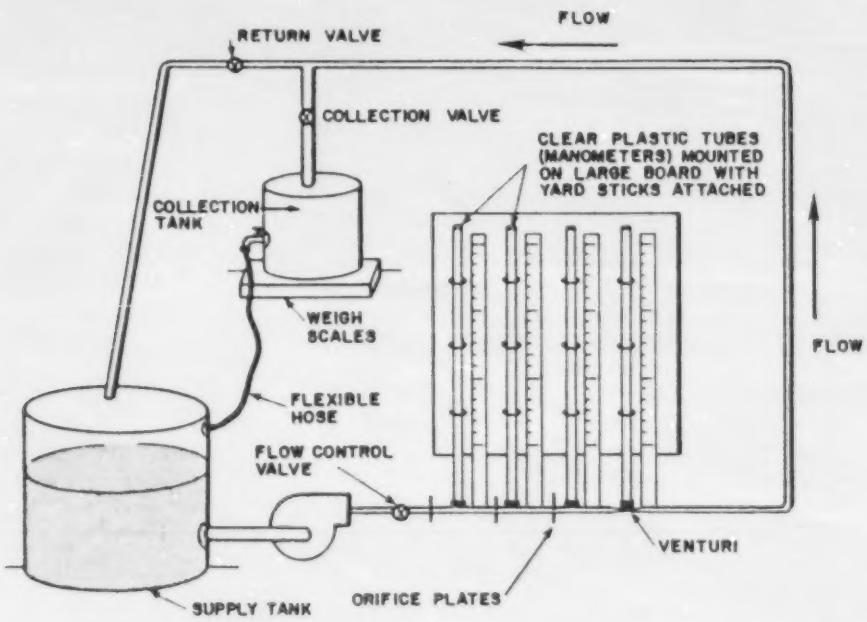


Figure 3-7-14. Flowmetering device.

2. Open control valve and return valve; allow water to flow to clear air pockets and sweep out bubbles; close control valve gradually to subject meter to increased pressure; when water level has risen to a convenient height in manometers, close supply valve.
3. Level the manometer water columns; open control valve to obtain a reasonably large Δh.
4. Measure pressure drops on meters (take at least 10 readings each); record readings on Data Table 3-7-1 (a and b).

5. Note and record pressure losses through metering system.
6. Use vendor-furnished discharge coefficients from specification sheets; calculate flow rates through flowmeters.
7. Explain any differences.

CALIBRATE ORIFICE METER AND DETERMINE ORIFICE COEFFICIENT

1. Arrange orifice meter in manner illustrated above. (Beyond control valve, a flexible hose should lead to a measuring tank.)
2. Admit water from supply valve into meter.
3. To establish orifice coefficient, obtain variations ($h_1 - h_2$) with discharge rate Q: open control and supply valves (to clear out air bubbles and pockets); gradually close control valve to subject meter to increased pressure; when water has risen to convenient heights in manometers, close supply valve; open supply and control valves to obtain flow.
4. Measure the flow rate (collect in weighing tank and take Δh readings); take approximately 10 Δh readings; record readings on Data Table 3-7-2; average flow rate.
5. Adjust flow and repeat 4, above.
6. Plot, on the charts provided, a D.P. versus flow curve; calculate orifice coefficient:

$$Q = CA_2 \sqrt{\frac{2g\ (h_1 - h_2)}{\rho\ [1 - (\frac{A_2}{A_1})^2]}}\ .$$

7. Plot, on charts provided, variation of C with Q.
8. What would be effect on results if piping were not level?
9. Discuss difference between calculated C and empirical value.

DATA TABLE

DATA TABLE 3-7-1a

MEASURE OF ORIFICE AND VENTURI PRESSURE DROPS

Orifice Plate I.D. _____ Area _____

Pipe I.D. _____ Area _____

Venturi I.D. _____ Area _____

Orifice C_o _____

Venturi C_v _____

Orifice Reading No.	h_1 (inches)	h_2 (inches)	Calculated Flow, ft^3/sec
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
Average			

DATA TABLE 3-7-1b

MEASURE OF ORIFICE AND VENTURI PRESSURE DROPS

Orifice Plate I.D. _____ Area _____

Pipe I.D. _____ Area _____

Venturi I.D. _____ Area _____

Orifice C_o _____

Venturi C_v _____

Venturi Reading No.	h_1 (inches)	h_2 (inches)	Calculated Flow ft^3/sec	% Difference Between Calculated Flows Using Orifice and Venturi
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
Average				

DATA TABLE 3-7-2

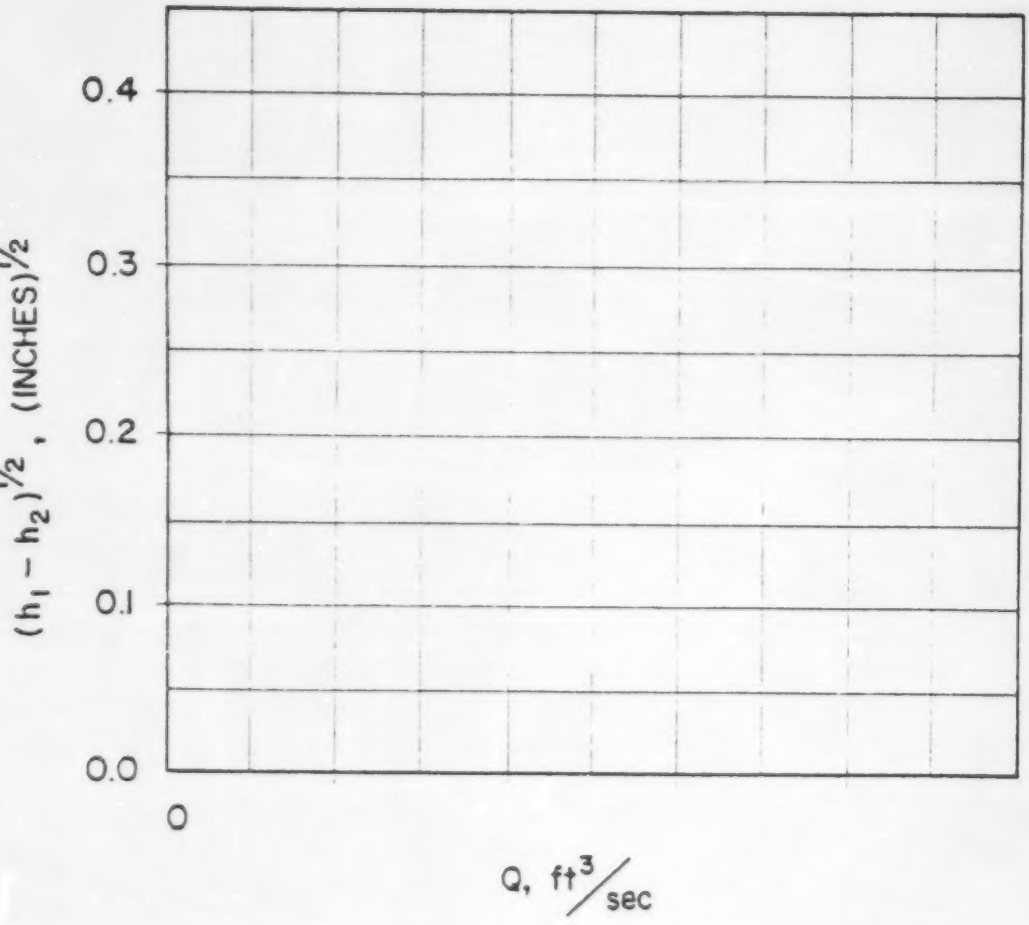
CALIBRATION OF ORIFICE PLATE

Orifice Plate I.D. _____ Area _____

Pipe I.D. _____ Area _____

Weight lbf	t sec	h_1 inches	h_2 inches	Q ft^3/sec	(h_1-h_2) inches	$(h_1-h_2)^{\frac{1}{2}}$ $(inches)^{\frac{1}{2}}$

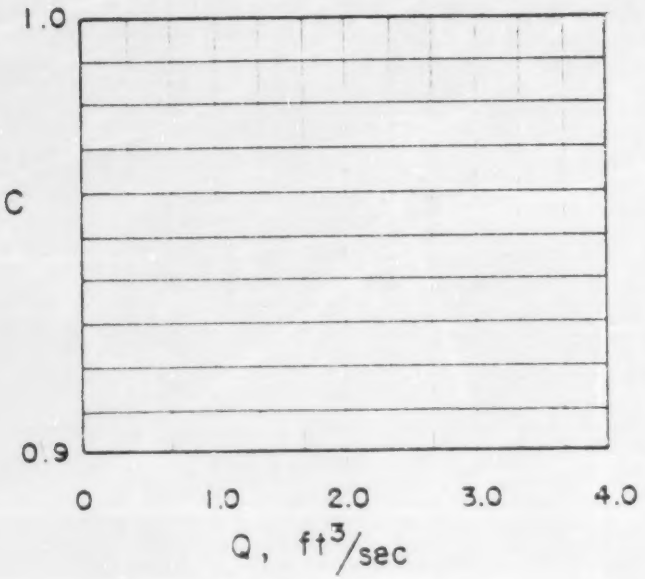
PLOT OF $(h_1 - h_2)^{\frac{1}{2}}$ vs. Q



VALUES OF "C" CALCULATED FROM INDIVIDUAL FLOWS

Q ft^3/sec	$(h_1 - h_2)^{\frac{1}{2}}$ $(inches)^{\frac{1}{2}}$	C

VARIATION OF C WITH Q



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TEST

Read each question carefully. Be sure your responses give the specific information each question requires. Your answers should be brief. Use the backs of the test if you need more space.

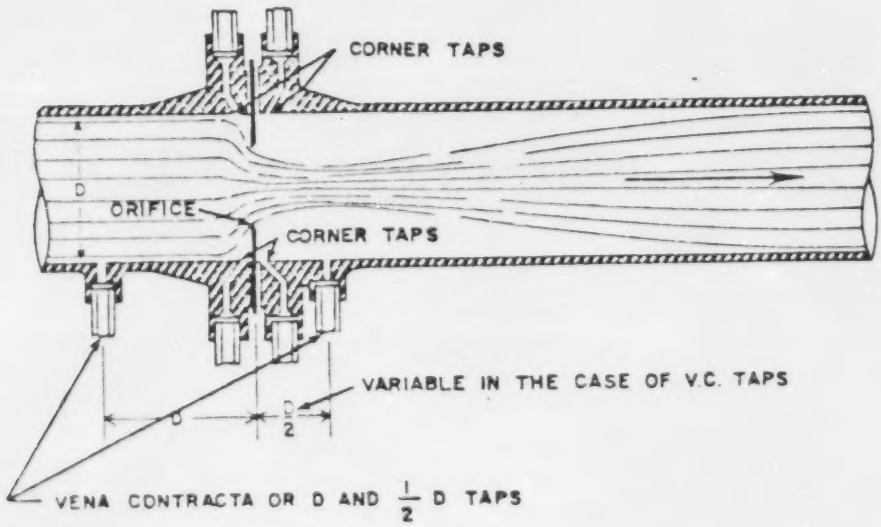
1. What physical properties of fluid are important in flow metering?

2. Why is velocity an important factor in flow metering? Describe flow when the average velocity of a fluid is slow. Describe flow as the average velocity increases from slow to fast.

3. What is a Reynolds number? What factors are considered (used) in calculating a Reynolds number?

4. What does a high Reynolds number, i.e., over 4000 indicate?

5. Here is a sketch of an orifice plate or meter.



Describe the flow's velocity as it reaches the orifice plate, as it reaches slightly downstream from the orifice plate, and as it gets further downstream from the plate.

6. In selecting an orifice plate, why is the ratio of the orifice plate opening to the internal diameter of the pipe a principal consideration?

7. What are taps and what is their purpose?

8. Why is a flow nozzle more likely to produce less convergence and less pressure loss than the orifice plate?

9. Compare the flow nozzle, Venturi tube, and orifice plate as to accuracy, use with high ratios of opening to internal diameter of pipe, and pressure recovery.

10. The Pitot tube does not actually measure flow rate. Exactly what does it measure?

11. Answer these questions about a Pitot tube:

    a. Describe a fluid's velocity and pressure as it contacts the Pitot tube.

    b. What is the purpose of the impact opening?

    c. What is the purpose of the pressure tap?

12. List six factors that should be considered in the installation of a primary element.

a. _____

b. _____

c. _____

d. _____

e. _____

f. _____

13. What is the purpose of the differential pressure (Delta ρ) cell?

_____

_____

14. What is the purpose of an integrator?

_____

_____

15. List five specific, typical applications of flow measurement.

a. _____

b. _____

c. _____

d. _____

e. _____

16. List two advantages and two disadvantages of the orifice plate, flow nozzle, and Venturi tube.

_____

_____

_____

_____

_____

_____

_____

_____

For the next two question, use the data given below to solve the problems. An electronic calculator may be used.

Given:

pipe I.D. = 6 inches

orifice I.D. = 3 inches

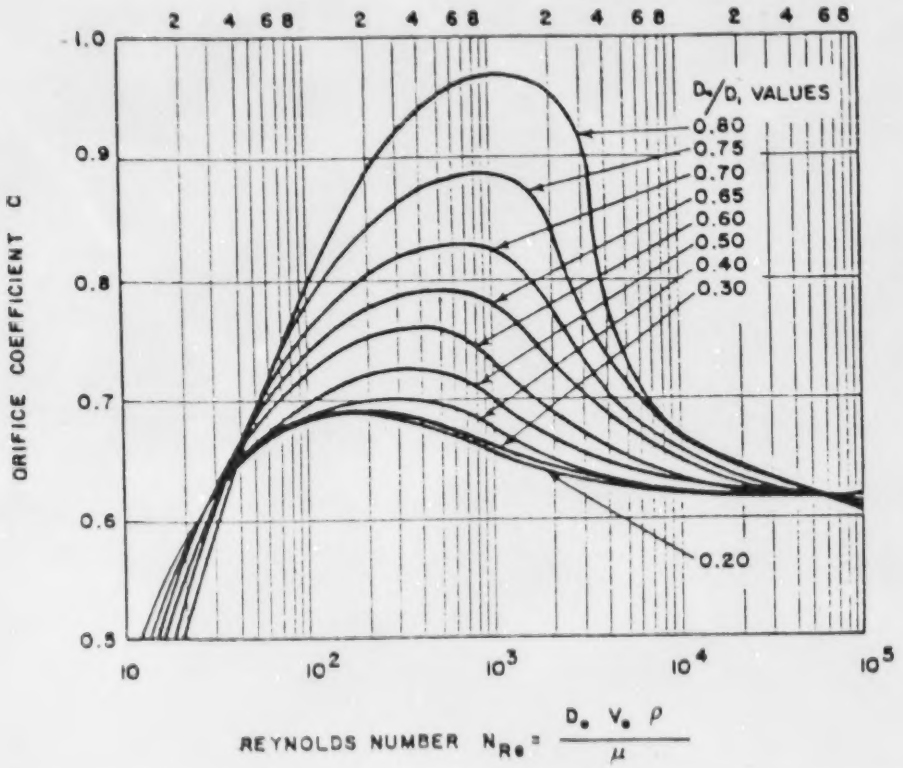
Reynolds No. = 1000

water density = 62.4 lbf/ft^3

1 ft^3 = 7.5 gallons

Area of Circle = πr^2

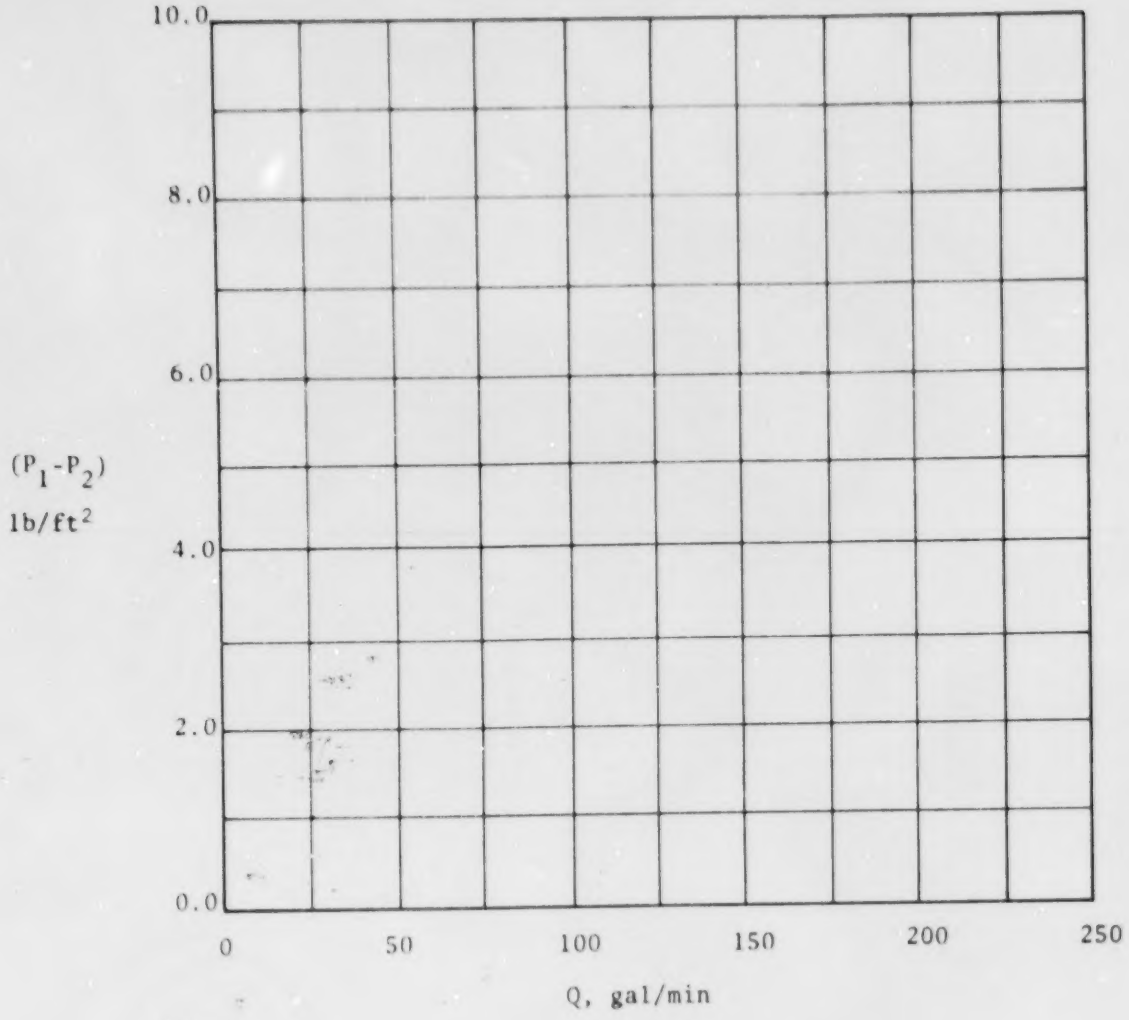
$$Q = CA\sqrt{\frac{2q(P_1 - P_2)}{P[(1 - (\frac{D_o}{D_1})^4)]}}$$



17. Calculate flow in gallons per minute for each of the following sets of differential pressures across the orifice plate.

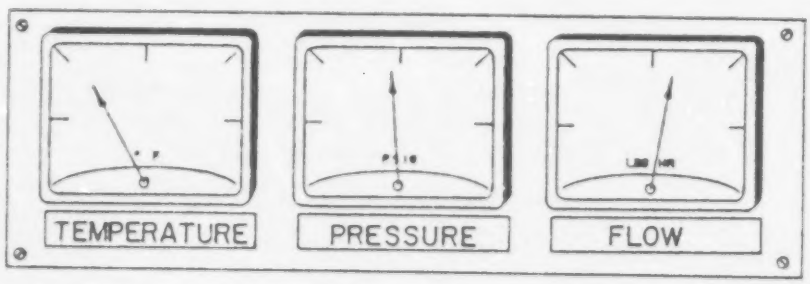
	Set #1	Set #2	Set #3
$(P_1 - P_2)$	2 lb/ft^2	6 lb/ft^2	10 lb/ft^2

18. Prepare a pressure/flow graph for the orifice plate by plotting the values obtained in question 17 on the following chart.



NUCLEAR TECHNOLOGY

MODULE 3-8 FLOW-SENSING DEVICES: LINEAR FLOWMETERS



PRINCIPLES OF
PROCESS INSTRUMENTATION

COURSE 3

COURSE MODULES

COURSE 3 PRINCIPLES OF PROCESS INSTRUMENTATION

MODULE 3-1	Temperature-Sensing Devices: Glass-Bulb Thermometers
MODULE 3-2	Temperature-Sensing Devices: Thermo-couples
MODULE 3-3	Temperature-Sensing Devices: Resistance Thermometers
MODULE 3-4	Temperature-Sensing Devices: Pyrometers
MODULE 3-5	Basic Principles of Flow Measurement
MODULE 3-6	Pressure-Sensing Devices
MODULE 3-7	Flow-Sensing Devices: Differential-Pressure Flowmeters
MODULE 3-8	Flow-Sensing Devices: Linear Flowmeters

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INTRODUCTION

This module defines certain basic terms used in discussions of linear flowmeters; it explains basic operating principles of specific types of primary elements and it discusses secondary elements, including their specific characteristics, applications, advantages and disadvantages, installations and operation, and maintenance of these devices.

Alignment (calibration) of these devices and the uses of standards are discussed in terms of power plant applications.

The laboratory procedure is intended to encourage the student to exercise laboratory procedures and experiences from preceding modules of this course. It leaves many details of equipment selection, setup and lineup, as well as data needs and acquisition, tables, and graphical presentations to the student's initiative.

MODULE PREREQUISITES

The student should have completed all previous modules in this course.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms (use appropriate units):
   - Linear flowmeter.
   - Volumetric flow rate.
   - Nutating.
   - Mass flow rate.
2. Discuss operating principles, descriptions, characteristics and applications of various linear-flow sensing meters; identify classifications of devices.
3. Discuss a) transducers and b) output units for linear devices.
4. Install each of three linear flowmeter types.
5. Calibrate each type; establish a calibration curve for each.

PRINCIPLES OF OPERATION: LINEAR FLOWMETERS

There are four basic categories of linear flowmeters:

Area meters.
Positive displacement (volumetric) meters.
Velocity meters.
Thermal meters.

In a linear flowmeter, there is a direct or linear relationship between flow rate and output from the flow measuring device. This simplified relationship eliminates the more complicated square-root extraction process associated with differential-pressure flowmeters.

Most linear flowmeters have volumetric outputs, but some are capable of mass-flow measurement. The latter is one of the most needed measurements in industrial processes. In power plants, mass flow is important in such systems as steam flow and feedwater flow measurements (where a "match" is required between these two flows to ensure safe and efficient operation of the plant).

Recall that fluid mass, not volume, determines its heat capacity, heat transfer characteristics and other critical properties. Mass is independent of physical properties of the matter itself, especially temperature.

Any flow-measuring device in which the reaction of a primary element is proportional to true mass flow is termed a "mass flowmeter."

Principles of operation of the four categories of linear flowmeters are given below.

AREA METERS

The variable-area flowmeter consists of a vertical, tapered glass (or metal) tube incorporated into a flow system so that its larger diameter is on the outlet side of the meter (Figure 3-8-1). Within the tube is a specially designed obstacle (float or piston), which is free to move up and down as upward flow rate in the tube changes. The

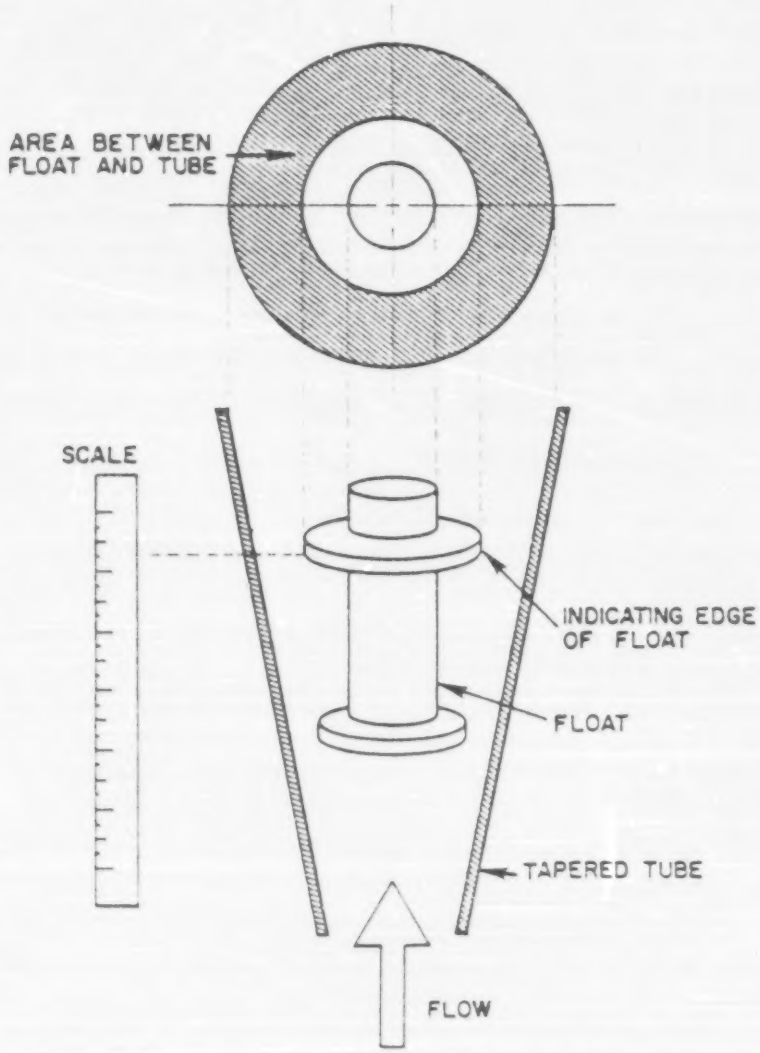

Figure 3-8-1.
Area flowmeter.

vertical, stationary float position is indicative of volumetric flow rate.

The theory of operation for an area (variable-area) flowmeter is basically the same as that for a differential-pressure meter, such as an orifice or nozzle. The relationship governing flow may be written:

$$Q = CA\sqrt{gh}$$ Equation 3-8-1 (Equation = Eq.)

where

Q = volumetric flow.
C = coefficient of discharge.
A = area of restriction (cross-sectional).
g = gravitational constant.
h = differential pressure (static) or head.

In the orifice meter and other head-type meters, rate of flow was indicated (inferred) by a differential pressure across a fixed-flow area; however, in area flowmeters, this area is a variable and pressure drop is relatively constant (i.e., does not change with flow rate). Thus, flow rate is indicated by size of area through which the fluid must flow.

This area is usually read by observing float position in a tube.

There are three general types of variable area flowmeters:

Rotameter.
Orifice and tapered plug meter.
Piston-type meter.

Rotameter

The rotameter consists basically of a plummet (or float) and a vertically mounted, tapered glass tube. Originally, the floats were produced with slots to give them rotation from centering and stability - thus the name. Present designs omit these slots.

Fluid enters the lower end of the tube and exerts a force on the float; the float rises until the annular space between float and tube is sufficient to permit a flow; this flow creates a differential pressure to balance the weight (less its buoyancy force) of the float (Figure 3-8-2).

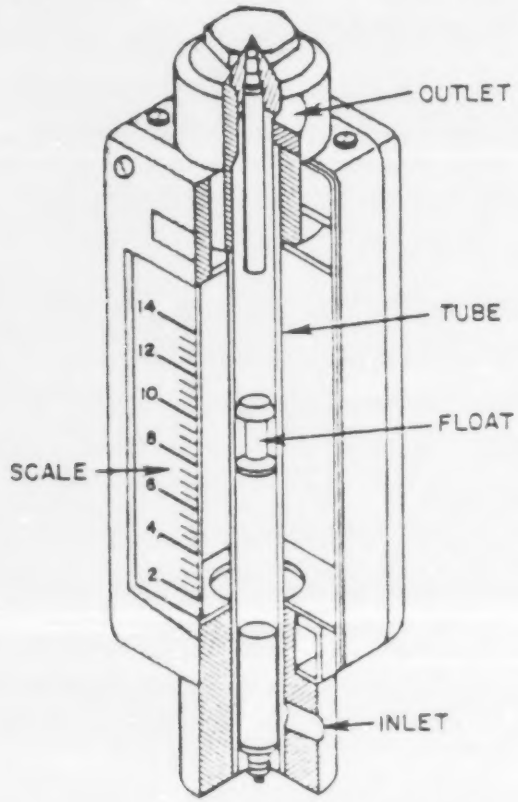

Figure 3-8-2. Area flowmeter (rotameter).

A scale marked on the outside allows flow rate to be read directly.

Rotameters are usually designed to be used with a particular fluid so that they can measure both volumetric and mass flow. For high-pressure applications, the rotameter tube is solid metal; thus, float position must be sensed by a magnetic pickup located external to the tube (Figure 3-8-3).

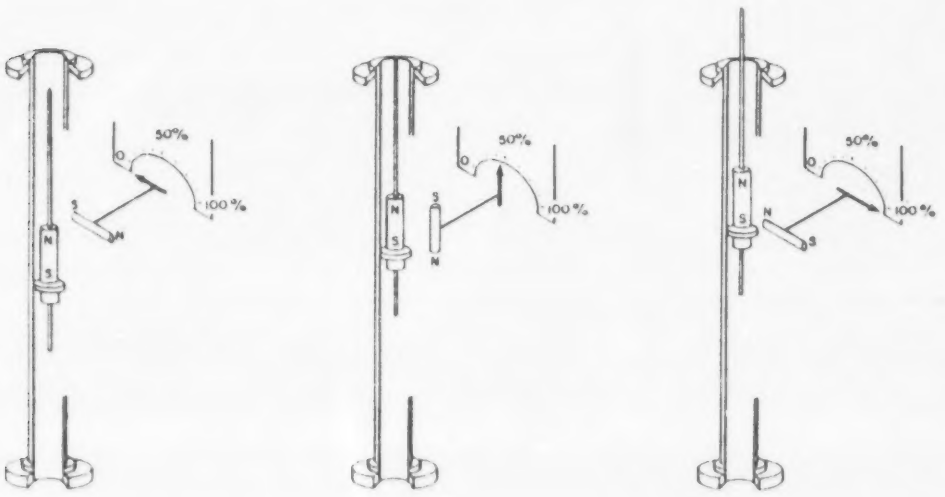

Figure 3-8-3. Metal tube rotameter. Magnet connected to indicator follows movement of magnet inside float. As float rises, indicator shows higher rate of flow. Float does not move up and down guide rod; entire assembly, including guide rod, moves with flow rate.

Piston-Type Area Meter

A piston-type area meter operates in a manner similar to the rotameter; however, it uses a sleeve (or cylinder), rigidly held in a cast body, and a well fitted, spring-

loaded piston (or metering plug) inside the sleeve (Figure 3-8-4).

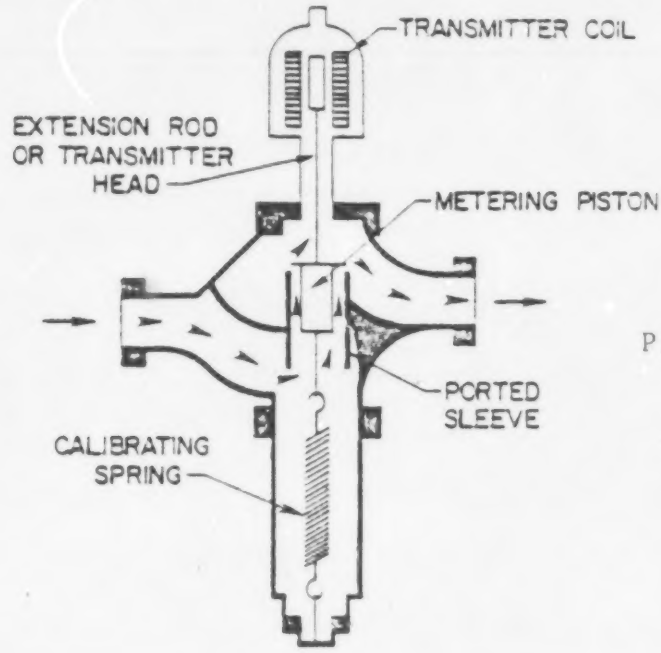

Figure 3-8-4.
Piston-type area meter.

Upward pressure of fluid lifts piston until ports in sleeve permit fluid flow. A calibrated spring pulls downward on piston to increase differential pressure beyond that which might result from the weight of movable meter parts.

The vertical position of the piston establishes spindle position, which extends through a packing gland to operate an indicating pointer or transducer.

Orifice-and-Tapered-Plug Meters

An orifice-and-tapered-plug meter is a special form of rotameter that operates on the same basic principles

(Figure 3-8-5). It is used when a high degree of accuracy is not required and compact size and cost are important.

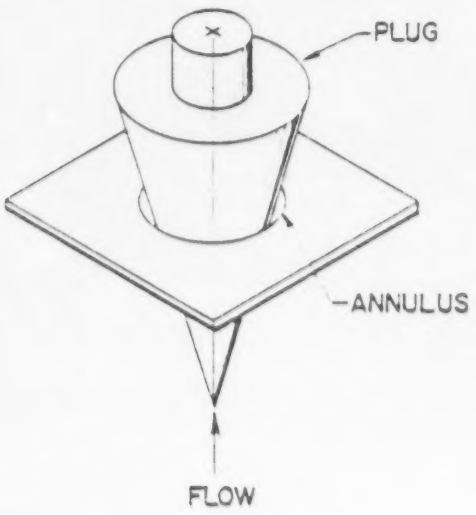

Figure 3-8-5.
Orifice-and-tapered-plug meter.

POSITIVE DISPLACEMENT

Positive-displacement (PD) flowmeters measure flow directly in discrete quantities by measuring chambers rather than by indirect or inferential means (Figure 3-8-5). The meter separates flow into measured volumes (not mass) by the use of pistons or vanes. A piston or vane covers a fixed path and, on each revolution of the meter, volume is counted.

By appropriate corrections for changes in density (caused by pressure) and for temperature and composition changes, a PD meter can indicate flow in terms of mass or weight. (These meters measure fluid volume, not flow rate; to find flow rate, volume is divided by time (i.e., count rate = counts/time).

Rotary Meter

A rotary meter uses two lobes or rotors mounted on parallel shafts. The shafts rotate in opposite directions like those in a diesel engine's supercharger, or a high-capacity rotary air compressor (Figure 3-8-6). These rotors

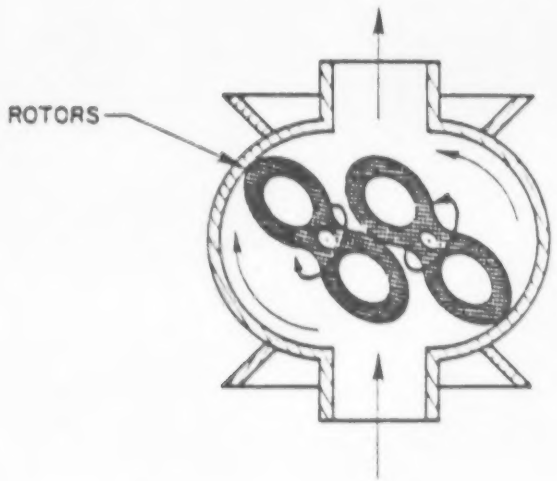

Figure 3-8-6.
Rotary meter.

have a set of timing gears at one end of the shaft, which gives relative motion to the lobes. Fluid enters the inlet and fills the space between the lobes and the meter housing. From there, it forces rotation of the lobes and leaves housing through the outlet. The volumetric displacement of the lobes drives a revolution counter attached to the shaft of one lobe. By measuring the known volume of an individual displacement, total quantity of flow can be measured.

To obtain the flow rate, a time factor must be incorporated into the meter design.

These meters are sometimes used in water, though they

are better adapted to oil and other lubricating liquids.

Wobble-Type Meters

Wobble-type volumetric meters are common adaptations of positive-displacement meters. They are used often in domestic water meters.

A wobble-type meter most often employs a nutating disk - a mechanical device with a metering chamber and a circulating disk fastened to a central ball (Figure 3-8-7).

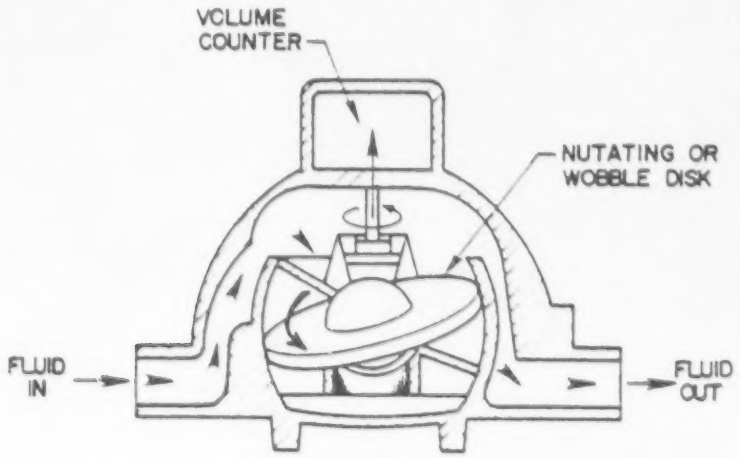

Figure 3-8-7.
Wobble-type meter.

The disk is free to wobble within the chamber, but it cannot rotate. Each cycle of the measuring disk displaces a fixed volume of fluid. The fluid enters through the inlet port and fills the space above and below the disk. The advancing volume of fluid moves the disk in a nutating motion (wobbling like a top) until the fluid is discharged from the outlet port. A shaft atop the central ball is always in an inclined position. The movable-disk chamber

has spherical sides, and conical top and bottom surfaces. The shaft can drive a series of gears, or it can act as a counter to indicate the number of revolutions, thus measuring the volume of fluid flowing through the meter. Its volumetric units ususlly are in gallons, cubic feet or liters.

VELOCITY METERS

Velocity meter design is based on the turbine principle (Figure 3-8-8). Fluid volume normally is measured by move-

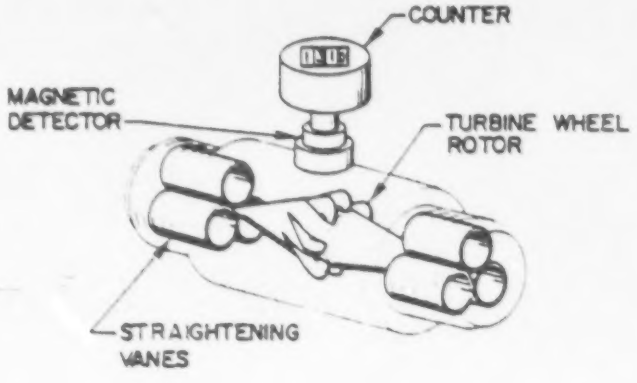

Figure 3-8-8.
Velocity meter.

ment of a vane, cup, wheel or turbine, with responses proportional to fluid velocity. Rotation of a turbine-like device generates a series of electrical pulses, or drives a gear train that couples to the secondary element.

THERMAL METER

A thermal meter transfers heat from a heating element to a flowing fluid. The cooling of the heating element by the flowing fluid, or the bulk-temperature rise of the fluid downstream, or the amount of energy required to maintain the heating element at a constant temperature can be measured and equated to mass flow. These devices measure mass flow (heat-transfer properties are dependent on fluid mass).

Thermal meters are divided into two classes: 1) thermal resistance meters, in which a cooling effect (of a fluid stream on a hot body or filament) is involved and, 2) bulk-heating meters, in which the effect of a measurable and known quantity of input heat to a fluid stream is involved (Figure 3-8-9).

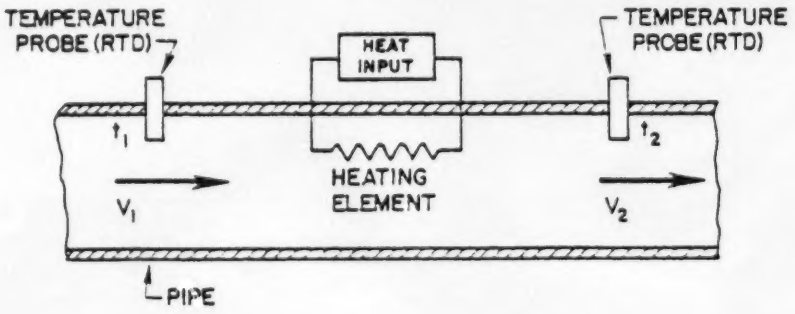

Figure 3-8-9. Bulk-heating thermal meter.

INSTALLATION AND OPERATION

In contrast to head-type flowmeters, most velocity meters require little flow streamlining. Velocity meters with turbines have built-in straightening vanes (thermal meters actually need some turbulence to ensure bulk-fluid mixing prior to downstream temperature sensing.)

In all linear flowmeter installations, it is essential that the devices have bypass lines with isolation valves and drains for use during maintenance. This is especially important when high-temperature, high-pressure, radioactive, toxic or corrosive fluids are in the lines.

EXERCISES

1. Develop a list of basic instructions (to be issued to a fellow worker) in the form of a work order to remove a PWR's primary coolant boric-acid nutating flowmeter.
2. Distinguish between mass and volumetric flowmeters.
3. Identify six day-to-day uses of linear flowmeters (e.g., household water meter).
4. Study flowmeter catalogs obtained from instructor. Given a set of purchase specifications (from instructor), choose flowmeter that best meets requirements.

MATERIALS

1 liquid linear flowmeter (variable-area, nutating and turbine), 0.5 - 1.0 gallon/minute (water).
1 specification sheet on each above flowmeter.
1 general assortment of hoses, clamps, piping, couplings, globe valves, air-vent valves and threaded couplings.
1 test tank, 5- to 10-gallon capacity.
1 calibration tank, 5-gallon capacity.
1 shop working-standard (water, rotameter type).
1 stopwatch.

PROCEDURES

CALIBRATE FLOW-TYPE LINEAR FLOWMETERS

1. Assemble one each variable-area, nutating (register-type counter) and turbine (register-type counter) meter in accordance with vendor instructions.
2. Draw piping schematic to provide flow data on all three meters concurrently during each calibration. (Note: The shop working-standard should also be placed in this series.)
3. Connect piping system as drawn.
4. Calibrate flowmeters by taking three or more data points for each flow rate (with concurrently measured volumes in the calibration tank).

5. Average data and plot indicated versus calibrated flows for each flowmeter. Plot shop working-standard flow on same graph.

DATA TABLE

To be developed by student.

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TEST

Read each question carefully. Be sure your responses give the specific information each question requires. Your answers should be brief. Use the backs of the test if you need more space.

1. Describe the relationship between flow rate and output in a linear flowmeter.

2. Describe the major difference between differential pressure instruments and variable area meters.

3. In the variable area flowmeter, what is the indication of flow rate?

4. Briefly describe the operation of the rotameter from the time fluid enters through readout.

5. How is the size of the area adjusted in the rotameter?

6. Briefly describe how the piston-type area meter operates.

7. When might an orifice and tapered plug meter be used instead of the rotameter?

8. Briefly describe how the positive-displacement flowmeter works.

9. What causes the disc in a wobble-type meter to nutate? What happens to the fluid as the disc nutates?

10. In a velocity meter, what determines the speed of the turbine wheel or propeller?

_____

11. What is mass flow measurement?

_____

12. What three things (factors) can the thermal meter measure and equate to mass flow?

_____

_____

_____

13. What is the purpose of having bypass lines with isolation values and drains in all linear flowmeter installations?

_____